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international centre for theoretical physics

SMR.1227 - 7

SUMMER SCHOOL ON ASTROPARTICLE PHYSICS AND COSMOLOGY

12 - 30 June 2000

DARK MATTER AND PARTICLE PHYSICS

Lectures I and II

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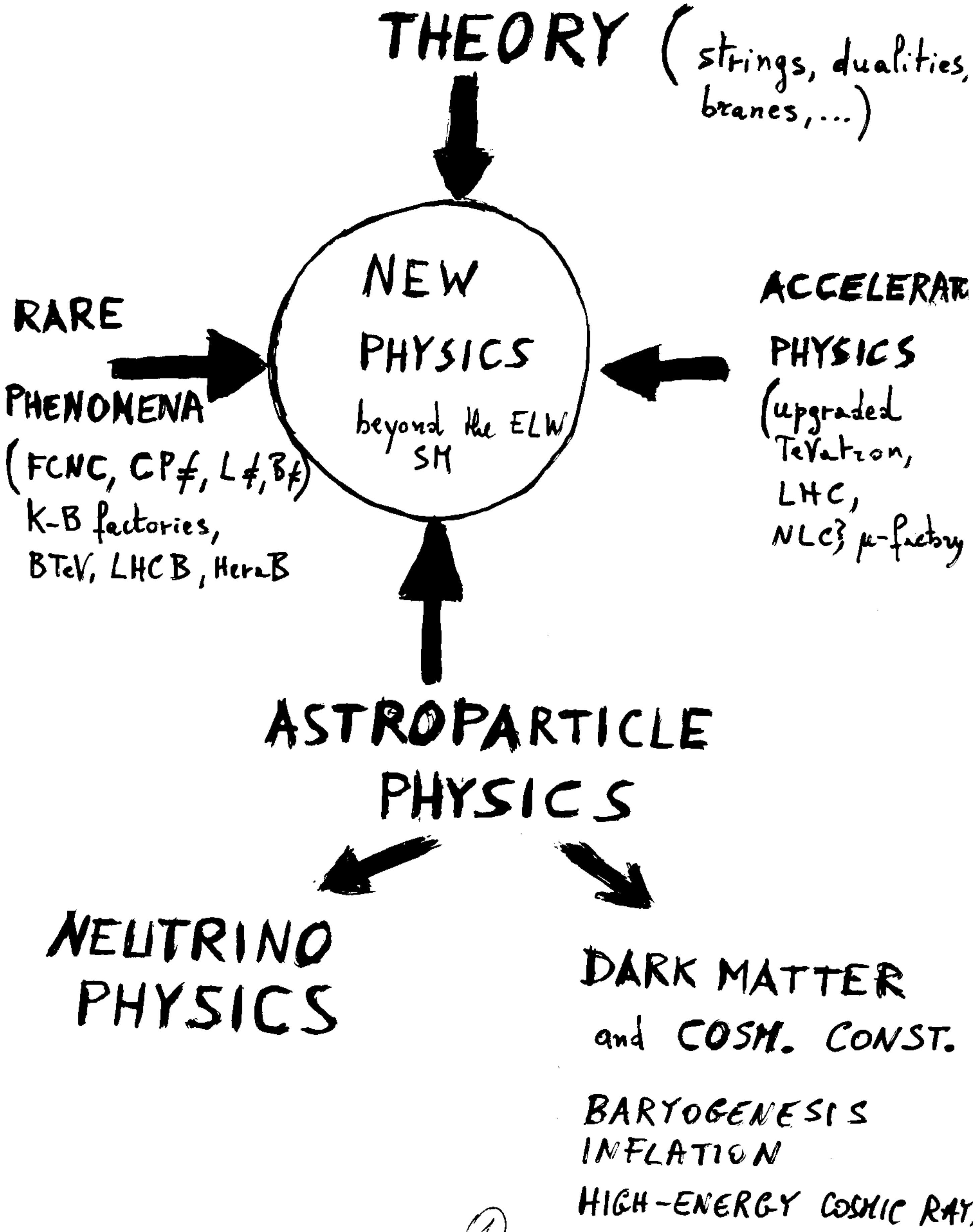
Please note: These are preliminary notes intended for internal distribution only.

A. MASIERO


THEORY (strings, dualities, branes, ...)
NEW PHYSICS
beyond the ELW SM
RARE PHENOMENA
(FCNC, CP̸, L̸, B̸)
K-B factories,
BTeV, LHCB, HeraB
ACCELERATOR PHYSICS
(upgraded TeVatron,
LHC,
NLC? μ-factory
ASTROPARTICLE PHYSICS
NEUTRINO PHYSICS
DARK MATTER and COSM. CONST.
BARYOGENESIS
INFLATION
HIGH-ENERGY COSMIC RAY.

THE STANDARD MODEL OF PARTICLE PHYS

- ELECTROWEAK INTERACTIONS SM → Glashow - Weinberg - Salam SM (GWS)
- STRONG INTERACTIONS → QCD

GWS SM and QCD are GAUGE THEORIES

↓

Local Symmetry

GWS SM → $SU(2)_L \times U(1)_Y$

QCD → $SU(3)_c$

[Global symm. : ex. $\bar{\psi}\,(\not\partial - m)\,\psi$

invariant under $\psi(x) \to e^{i\alpha}\psi(x)$

the phase α is the same $\forall x$

Local symm. : ask for invariance under

$$\psi(x) \to e^{i\alpha(x)}\,\psi(x)$$

α depends on x

$$\bar{\psi}(\not\partial - m)\,\psi \Rightarrow \bar{\psi}\,(\not D - m)\,\psi$$

↳ covariant derivative

$\partial_\mu \to \partial_\mu - ie A_\mu$ ↳ vector compensating field

$SU(2)_L \rightarrow$ 3 vector (gauge) fields $W^1_\mu, W^2_\mu, W^3_\mu$

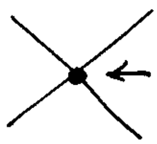
$U(1)_Y \rightarrow$ 1 " " " B_μ

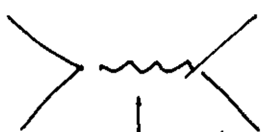
$SU(3)_c \rightarrow$ 8 " " " $\lambda^a_\mu \quad a = 1, \dots, 8$

(vector (gauge) fields in the adjoint representation)

Exact Gauge Symmetries → Renormalizable ☺
→ Massless gauge bosons ☹

weak interactions need massive vector bosons

Fermi theory  ← point-like interactions



↓ intermediate vector boson

How to break a gauge theory without spoiling its renormalizability ?

$\Downarrow$

SPONTANEOUS BREAKING OF GAUGE SYMM. $\Rightarrow$ HIGGS MECHANISM

explicit breaking : add $H^2 W_\mu W^\mu$
spoils renormaliz.

spontaneous breaking :
$\mathcal{L}$ invariant, vacuum is not invariant
(ex. : $\mathcal{L} = \partial_\mu \varphi \partial_\mu \varphi^* + V(\varphi)$
$V(\varphi) = -\mu^2 |\varphi|^2 + \lambda |\varphi|^4$)

spont. break. of a global symm : Goldstone bosons
$G \to G'$ # Goldst. bosons = # of generat in G/G'

spont. break. of a gauge theory :
Goldst. bosons "eaten up" by the gauge bosons (they become their longitudinal compon.
$\Rightarrow$ Higgs mechanism

$SU(2)_L \otimes U(1)_Y \Longrightarrow U(1)_{em}$

Higgs doublet H $D_\mu H \, \partial_\mu H^+ + \mu^2 HH^+ - \lambda (HH^+)^2$

$\Rightarrow \langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$

W^+, W^-, Z^0 massive
γ massless

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FERMION MASSES

Lor. group $SU(2) \times SU(2)$

2-compon. Weyl spinor $\chi \; (\frac{1}{2}, 0) \xrightarrow[\text{conjug. same 2 comp}]{} \bar{\chi} \; (0, \frac{1}{2})$

$\eta \; (0, \frac{1}{2}) \quad \bar{\eta} \; (\frac{1}{2}, 0)$

Given the two 2-compon. Weyl spinors χ and η, what are the possible fermion mass terms ?

1) $\chi^{\alpha} \chi^{\beta} \varepsilon_{\alpha\beta}$ $\quad (\alpha, \beta = 1, 2 \quad SU(2)$ indices$)$

$\eta^{\dot\alpha} \eta^{\dot\beta} \varepsilon_{\dot\alpha\dot\beta}$ $\quad$ These mass terms involve only 2 COMPONENTS

$\Rightarrow$ MAJORANA MASS TERMS

obtained coupling a spinor with itself

2) $\chi^{\alpha} \bar{\eta}^{\beta} \varepsilon_{\alpha\beta}$ $\quad$ DIRAC MASS TERMS

2 + 2 = 4 components

$\bar{\chi}^{\dot\alpha} \eta^{\dot\beta} \varepsilon_{\dot\alpha\dot\beta}$ $\quad$ bilinears formed with two independent spinors

FERMION MASSES IN SM

MAJORANA MASSES IMPOSSIBLE FOR EL. CHARGED FERMIONS ($\chi\chi$ carries $Q \neq 0$ if χ is charged) since $U(1)_Q$ is an exact symmetry

only candidate for Major. mass : neutrino

$\underbrace{\nu^\alpha \nu^\beta}_{T_3=+1} \varepsilon_{\alpha\beta}$ but ν carries $T_3 = +\frac{1}{2}$

$\rightarrow$ SU(2) forbids this term

DIRAC MASSES :

ex. $\bar{u}_L u_R$ $\qquad Q=0$ so $U(1)_Q$ does not forbid these terms

BUT $\bar{u}_L$ in SU(2) doublet, u_R in SU(2) singlet

SU(2) forbids all the fermionic mass terms

$\Rightarrow$ GAUGE INVARIANCE $SU(2) \times U(1)$ FORBIDS BOTH MAJOR. AND DIRAC MASSES IN $\mathcal{L}$

HENCE NO <u>DIRECT</u> FERMION MASS TERM CAN BE ADDED TO $\mathcal{L}_{SM}$

SINCE $SU(2) \times U(1)$ prevents the appearance of m_f $\Longrightarrow$ MAKE m_f appear after spontaneous breaking of $SU(2) \times U(1)$

$$\bar{\Psi}_L \quad H \quad \psi_R$$

$\bar{\Psi}_L \downarrow$ SU(2) doublet

$H \downarrow$ SU(2) doublet

$\psi_R \downarrow$ SU(2) singlet

spont. breaking $\langle H^0 \rangle \neq 0 \Longrightarrow m \, \bar{\Psi}_L \psi_R$

$$\mathcal{L}_{YUKAWA} = h_U \, \bar{Q}_L H u_R + h_D \, \bar{Q}_L \tilde{H} d_R + h_L \, \bar{L}_L \tilde{H} e_R + h.c.$$

$$\tilde{H} = i \tau_2 H^* \qquad H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix} ; \qquad \tilde{H} = \begin{pmatrix} H^+ \\ -H^{0*} \end{pmatrix}$$

N.B. : NEUTRINOS MASSLESS

NEUTRINO MASS

S.M. : ν_L no ν_R only φ $SU(2)_L$ doublet in the scalar sector

why?

Majorana mass : ENLARGEMENT OF THE HIGGS SECTOR

$\nu_L \nu_L$ transforms as the $T_3 = +1$ of an $SU(2)_L$ triplet

→ gauge invar. requires $\Delta \equiv SU(2)_L$ scalar triplet

$\underbrace{\nu_L \nu_L}_{\text{triplet}} \Delta \rightarrow SU(2)_L$ singlet

↓ after S.S.B. $\langle \Delta \rangle$

Alternatively: $\nu_L \nu_L \varphi \varphi$ non-renorm. term from some fundam th.

Dirac mass : $m \, \bar{\nu}_L \nu_R$ ENLARGEMENT OF THE FERMION SECTOR

requires $(\nu^c)_L$ or ν_R

⇒ $\boxed{\text{in SM } \nu \text{ is rigorously massless!}}$

at any order in perturbation theory

$L \!\!\!/$ $\nu_L \, \nu_L \to$ triplet

$$\nu\nu \underbrace{\phi\phi}_{\text{triplet}} \Rightarrow \text{dim. } 5 \qquad 1/M$$

$$m_\nu \sim e^2 \, G_F^{-1}/M$$

(if ϕ not elem $\phi \sim \langle \psi \bar{\psi} \rangle$ dim $\frac{3}{2} \times 6 = 9$

$m_\nu \sim e^4 G_F^{-3}/M^5$)

$L_e, L_\mu, L_\tau \not$: $\mu \to e\gamma$

$\underbrace{(\bar{l}_{\mu_L} \phi \sigma_{\mu\nu} e_R)}_{\text{dim } 6} B^{\mu\nu}$ $\pi^0 \to \mu^- e^+$, $K^0 \to \mu^- e^+$

$\tau^0 \to \mu^- e^+ \ldots$

$\underbrace{(\bar{l}_{\mu_L} \gamma_\alpha l_{e_L})(\bar{q}_L \gamma^\alpha q_L)}_{\text{dim } 6}$ $\left(BR(\mu \to e\gamma) < 10^{-11}_{\text{exp}}\right)$

ACKARD | PACKARD | PACKARD | PACKARD

SM

$SU(2) \times U($

GAUGE GROUP
SPONTANEOUSLY
BROKEN GAUGE THEOR.

MATTER

fermions quarks
leptons

scalars Higgs

$Q\ {+2/3}$

$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R \quad d_R \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R$

$Q = -1/3$

$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R \quad s_R \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \mu_R$

$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R \quad b_R \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \tau_R$

SU(2) doublet

SU(2) singlet

no ν_R

$Q = T_3 + Y$ $\quad m_\nu = 0$

$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$ higgs doublet

ONLY MISSING ACTOR OF THE PLAY

RADIATION

gauge vector
bosons

(messengers of the interaction

$SU(2)$

$W^+ \ W^- \ W^0$

$U(1)$

B^0

$SU(3)_c$

$g^a \quad a = 1, \dots, 8$
gluons

after SSB: $SU(2) \times U(1)_Y \to U(1)_{em}$

$W^+ W^- Z^0 \ , \ \gamma \ ,$
g^a

PARTICLE PHYSICS TESTS OF THE SM

- PRECISION TESTS → some observables tested at LEP with ‰ precision without any appreciable deviation from the SM expectation

  ⇓

  ANY NEW PHYSICS <u>MUST</u> "REPRODUCE EXACTLY" THE SM AT 100 GeV

- ANOMALIES (facts not expected in the SM) → R_b, 4-jet events, ... (gone)

  HERA anomalous events at high q^2 (gone)

  $e^+e^-\gamma\gamma$ " CDF event (no other events in the new run)

- RARE PROCESSES (highly suppressed or forbidden in the SM) → flavour changing neutral current (FCNC) phenomena, CP violation

  ex. $K-\bar{K}$, $B-\bar{B}$ mixings, $b\to s\gamma$

  $BR(\mu\to e\gamma)$, d_n^e, ...

  all results compatible with SM expectations

  ↓

  places where new physics BSM can compete fairly with SM

➡ NO INDICATION OF NEW PHYSICS BEYOND THE SM FROM EXP. PARTICLE PHYSICS

1. **WHY** PHYSICS BEYOND THE SM

EXPERIMENTAL NEEDS

- → PARTICLE PHYSICS
- → PARTICLE + ASTRO PHYSICS
- → PARTICLE PHYSICS + COSMOLOGY

THEORETICAL NEEDS

- → INTRINSIC INCONSISTENCI OF THE MODEL
- → SHORTCOMINGS (FAILURES TO ANSWER SOME QUESTIONS WE CONSIDER FUNDAMENTAL
- → FINE-TUNINGS

ASTROPARTICLE HINTS

OF PHYSICS BEYOND THE SM

COSMOLOGY ($\boxed{\text{SM}}$ of the BIG BANG)

GWS $\boxed{\text{SM}}$

ASTROPHYSICS ($\boxed{\text{SM}}$ of the SUN) ...

$\searrow \quad \downarrow \quad \swarrow$

MANY EXAMPLES OF MUTUAL SUPPORT

(ex. # neutrino species from nucleosynthesis and LEP)

BUT ALSO CLASHES POINTING (hopefully)

TO NEW PHYSICS BEYOND THE $\boxed{\text{GWS SM}}$

COSMOLOGY $\downarrow$ GWS $\downarrow$ ASTROPHYSICS

clashes

BARYOGENESIS
DARK MATTER
INFLATION

SOLAR ν ANOMALY
ATMOSPHERIC ν ANOMALY

BARYOGENESIS

- No evidence of antimatter within the solar system

- $\bar{p}$'s in cosmic rays → in agreement with production as secondaries in collisions

- if in cluster of galaxies certain galaxies were of matter and others of antimatter ⇒ the γ flux produced by $p\bar{p}$ annihilations in the cluster would exceed the observed γ flux

- if $n_b = n_{\bar{b}}$ and they are not separated well before they decouple we would be left with $(n_b - n_{\bar{b}})/n_\gamma$ several orders of magnitude smaller than $n_b/n_\gamma \sim 10^{-10}$

- if b and $\bar{b}$ are separated earlier → domains of b and $\bar{b}$ are too small today to explain separations larger than the supercluster size

→ ONLY MATTER IS PRESENT

→ HOW TO PRODUCE DYNAMICALLY A Baryon-Antibaryon ASYMM. STARTING FROM A SYMMETRIC SITUATION

SACKAROV'S CONDITIONS FOR BARYOGENESIS

- $\cancel{B}$ INTERACTIONS
- C, CP $\cancel{}$ INTERACTIONS
- OUT OF EQUILIBRIUM

in SM :

$\cancel{B}$ → although B number is conserved at any order in perturbation theory
NON-PERTURB. QUANTUM EFFECTS VIOLATE B

$\cancel{CP}$ → NOT ENOUGH to produce $n_B/n_\gamma \sim 10^{-10}$

out of equilibrium + demand that ΔB which is produced is no longer erased → NO 1st ORDER PHASE TRANS. → NOT ACHIEVED m_H TOO LARGE

⟹ ALTHOUGH $\cancel{B}$ INTERACTIONS OF THE SM MAY ERASE A PREVIOUSLY GENERATED **ΔB** THEY ARE **NOT** ABLE TO PRODUCE A MATTER-ANTIMATTER ASYMMETRY

THE DM PROBLEM

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

$0.4 < h < 0.9$

↪ '98 $h = 0.65 \pm 0.1$

* $\boxed{\Omega \geq 0.1}$ galactic rotation curves

* $\boxed{\Omega \gtrsim 0.3 - 0.4}$ clusters and superclusters

* $\boxed{\Omega_{LUMINOUS} < 0.01}$ total luminous mass density

* $0.01 \leq \Omega_{baryons} h^2 \leq 0.015$

from nucleosynthesis

$$\Downarrow$$

$$\boxed{0.01 < \Omega_{baryons} < 0.1}$$

∃ baryonic DM (Machos ...) ∃ **NON**-BARYONIC DM

* $\boxed{\Omega \simeq 1}$ favoured by $\begin{cases} \text{INFLATION} \\ \text{"NATURALNESS" arguments} \end{cases}$ + CMB data

* $\boxed{\Omega h^2 \leq 1}$ ($\tau_{univ} > 10^{10}$ yrs.)

$\Omega_{\text{"THEORISTS"}} = 1$!

$$\left(\frac{\dot{R}}{R}\right)^2 \equiv H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{R^2}$$

$$\Omega \equiv \rho/\rho_c \qquad H^2 = \frac{8\pi G_N}{3}\rho_c$$

$$\Omega(t) = \frac{1}{1 - \dfrac{k/R^2}{\frac{8\pi G_N}{3}\rho}}$$

$\rho \propto R^{-4}$ radiation-dominated Univ.

$\rho \propto R^{-3}$ matter - " "

to have $\Omega = O(1)$ today one must impose

$$|\Omega - 1| < 10^{-60} \text{ at } t_{\text{Planck}} \sim 10^{-43}\text{ s.}$$

IF INFLATION IS PRESENT $\Rightarrow \Omega \simeq 1$ predicted (in a "natur way)

during inflation H - const $\Rightarrow R = R_0 e^{Ht}$

k/R^2 negligible $\Rightarrow \Omega \simeq 1$

$$\Omega_0 = \Omega_M + \Omega_\Lambda$$

Ω_0 ↓ BEST DETERMINATION FROM ANISOTROPY OF **CBR**

Ω_M ↓ 0.4 ± 0.1 (baryon fraction method)

Ω_Λ ?

at last scattering Baryons coupled to γ: B fall into DM potential wells → γ pressure acts as a restoring force → gravity-driven acoustic oscillations

↳ Fourier modes with $k \sim \ell \frac{H_0}{2}$

➡ SERIES OF ACOUSTIC PEAKS STARTING AT $\ell \sim 200$

POSITION OF THE FIRST PEAK $\ell \simeq \frac{200}{\sqrt{\Omega_0}}$

⬇

$$\text{CBR} \rightarrow \Omega_0 = 1 \pm 0.2$$

?

Lineweaver '98

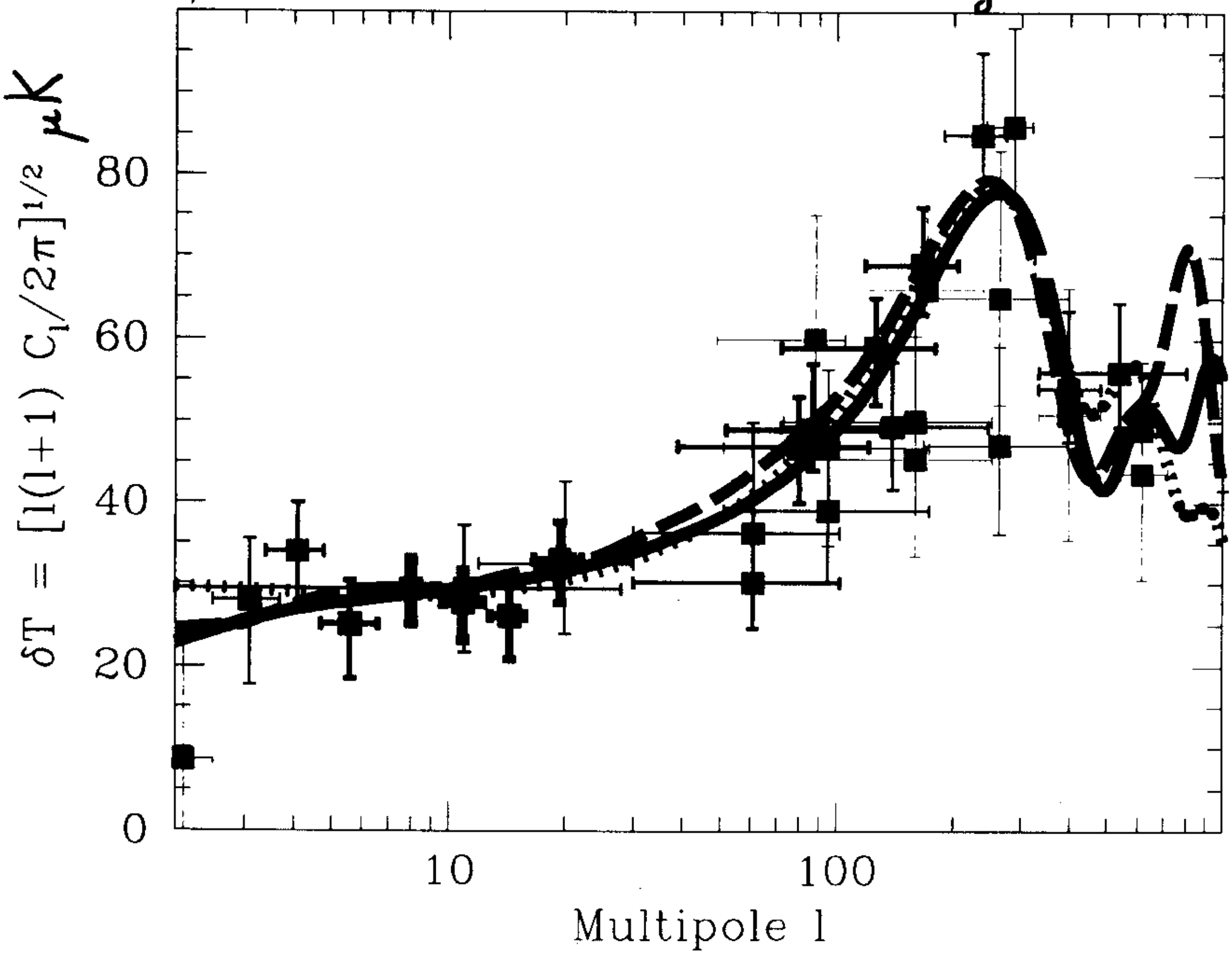
↳ pre. Boom

position of the 1st peak is insensitive to the composition of Ω_M and Ω_Λ, only to their sum

COBE MOST PRECISE COVERS MULTIPOLE $\ell \sim 2-20$

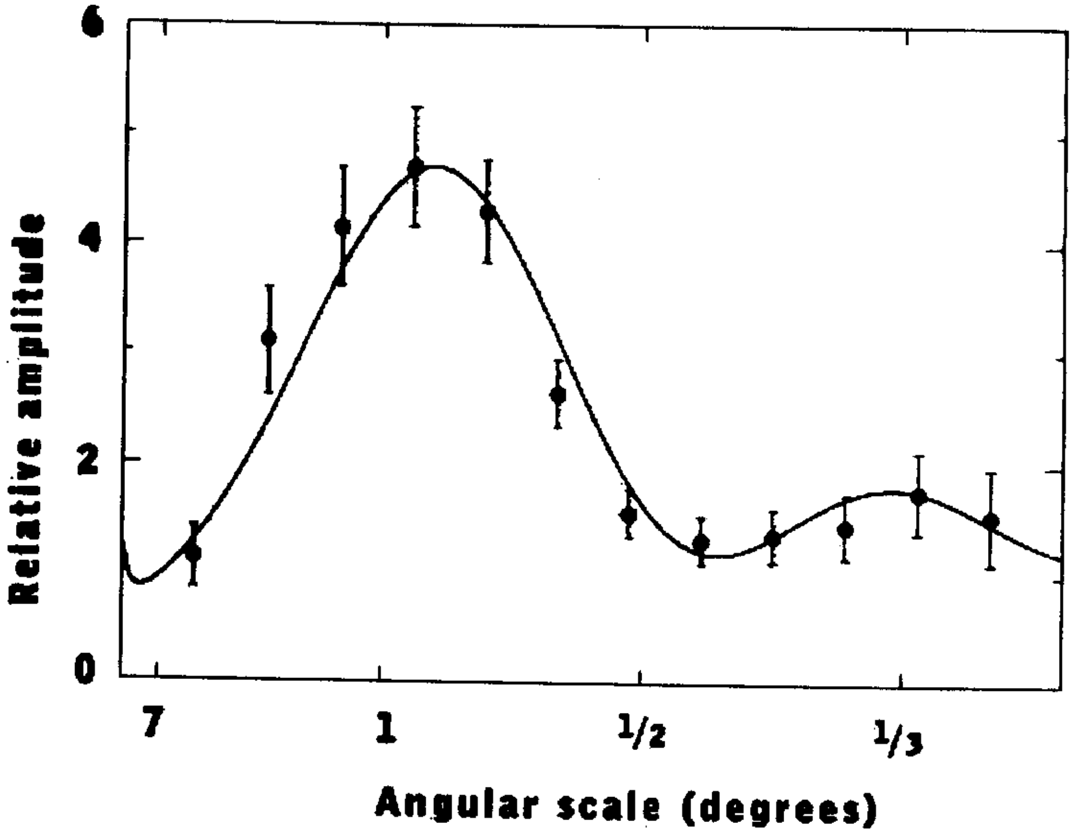
OTHER MEASUREMENTS FROM BALLOON-BORNE, ANTARCTICA-BASED, GROUND-BASED EXPTS.
USING LOW-FREQUENCY ($f < 100$ GHz) and HIGH-FREQUENCY ($f > 100$ GHz)

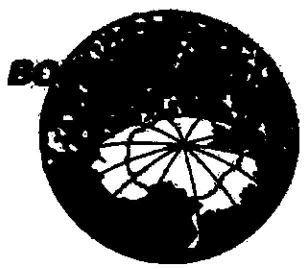
Tegmark '98



SATELLITES { MAP (NASA) late 2000
PLANCK (ESA) 2007

resolution ~ 30 times better than COBE (~0.1°)
map entire CBR sky





The Spectrum of Primordial Sound. The temperature variations in early universe seen in the BOOMERANG images are due to sound waves in the primordial plasma. The angular spectrum of these images shown here, reveals the characteristic size of the structures that dominate the image. A peak in this spectrum at scales of ~ 1 degree, as is seen here in the BOOMERANG data, indicates that the Universe is nearly spatially flat. The data can be well fit by cosmological models that contain non-baryonic matter in addition to normal, baryonic matter. One such model is indicated by the solid blue curve. A generic feature of such models is the presence of a harmonic series of additional peaks beyond the fundamental peak at ~ 1 degree. The relative height of the second peak at ~ 1/2 degree on the sky varies with the ballance of matter in the Universe contained in normal or baryonic matter and non-baryonic matter.

$$\ell_{peak} = (197 \pm 6) \quad (1\sigma \text{ error})$$

FROM OBSERVATIONS

$\Omega_M \sim 0.4$

$\Omega_0 = \Omega_M + \Omega_\Lambda \simeq 1$

$\exists$ of DARK, EXOTIC FORM OF ENERGY SMOOTHLY DISTRIBUTED (UNCLUSTERED)

$$\Omega_\Lambda \neq 0 \quad \text{with} \quad \Omega_\Lambda \sim 0.6$$

IS IT POSSIBLE TO TEST IT ?

→ main signature :
ACCELERATING (instead of de-accelerating
UNIVERSE

try to measure q_0

$$R^2_{curv} = \frac{H_0^{-2}}{\Omega_0 - 1} \quad ; \quad q_0 \equiv -\frac{(\ddot{R}/R)_0}{H_0^2} = \frac{1}{2}\Omega_0 + \frac{3}{2}\Omega_i w$$

$p_i = w_i \rho_i$ ($w_i = 0$ baryons ; $w_i = 1/3$ rad ; $w_i = -1$ cosm cons

Einstein eq. for an isotropic and homogeneous Universe

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3} - \frac{k}{R^2}$$

signature of the 3-curvature

expansion rate

cosmic scale factor

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho_{matter} - 2\rho_\Lambda\right)$$

$\rightarrow$ for $\rho_\Lambda > \frac{1}{2}\rho_{matter}$ the expansion of the Universe ACCELERATES !

Ω_Λ

TO AVOID INTERFERING WITH STRUCTURE FORMATION

(UNIVERSE MUST HAVE BEEN MATTER DOMINATED FROM THE EPOCH OF MATTER-RADIATION EQUALITY UNTIL VERY RECENTLY) $\Rightarrow$ Λ form of energy must be less important in the past than it is today

eq. of state: $p_\Lambda = w_\Lambda \rho_\Lambda \Rightarrow \rho_\Lambda \propto R^{-n}$ (R → UNIV. SCALE FACTOR)

$$n = 3(1 + w_\Lambda)$$

to be less important in the past $\Rightarrow$ $n < 3$, i.e. $w_\Lambda < 0$

ex.: cosmological const. $w_\Lambda = -1$

bonus: $H_0 t_0 \uparrow$ with $w \downarrow$ $\Rightarrow$ older Univ. for a given h_0
(no "age crisis")

$$q_0 = \frac{1}{2}\Omega_M - \Omega_\Lambda \sim -0.4$$ (from obs. values of Ω_M and Ω_0)

$\downarrow$

EVIDENCE FOR THIS "SMOKING GUN" FROM SNe Ia

MEASURING q_0

Expansion of the Universe is just a conformal scaling up of all distances:

$$v = H_0 d \quad \text{(Hubble law)}$$

$\Rightarrow$ if the distances and velocities to distant galaxies were all measured at the present then they would obey $v = H_0 d$

but we see distant galaxies at an **earlier time**

and so $\Rightarrow$ if the expansion is SLOWING their velocity should be ABOVE the Hubble-law prediction

$\Rightarrow$ if the expansion is SPEEDING UP their velocity should fall BELOW the Hubble-law prediction

magnitude-redshift Hubble diagram for ~50 SNe Ia out to z of nearly 1

$\Downarrow$

this is what was found by the

two groups $\begin{cases} \text{SUPERNOVA COSMOLOGY PROJECT} \\ \text{HIGH-Z SUPERNOVA SEARCH} \end{cases}$

TURNER 98

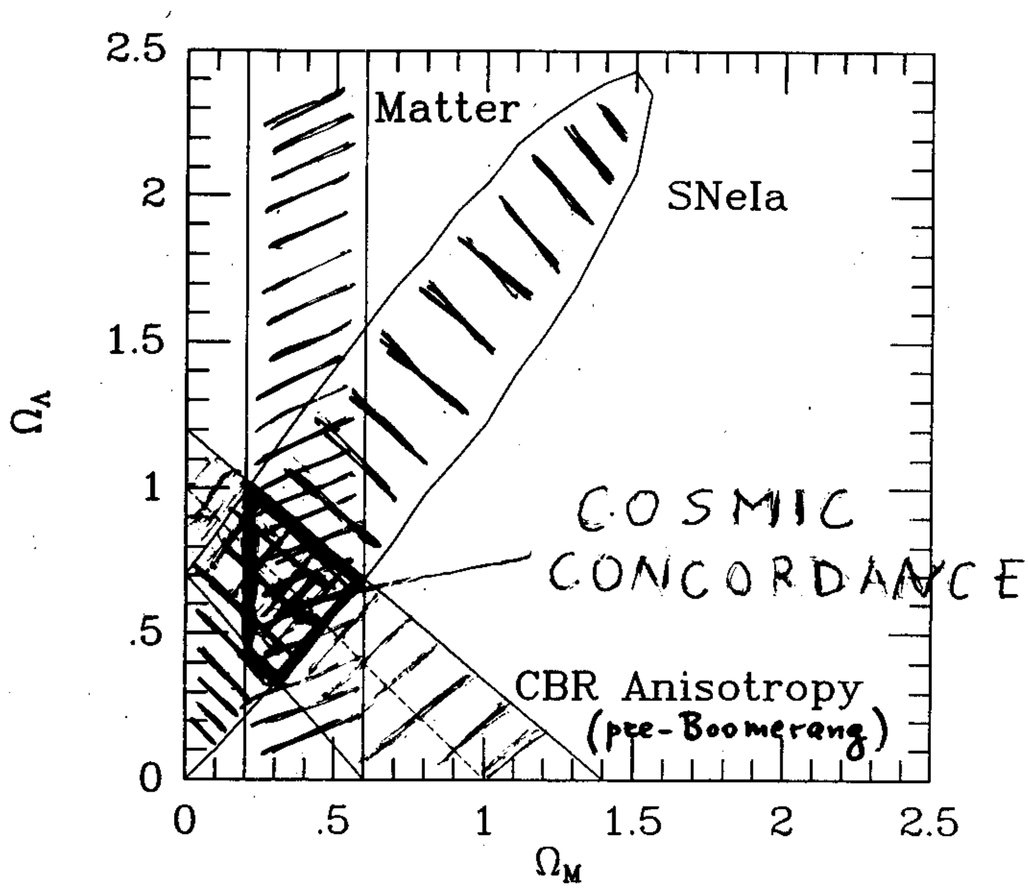
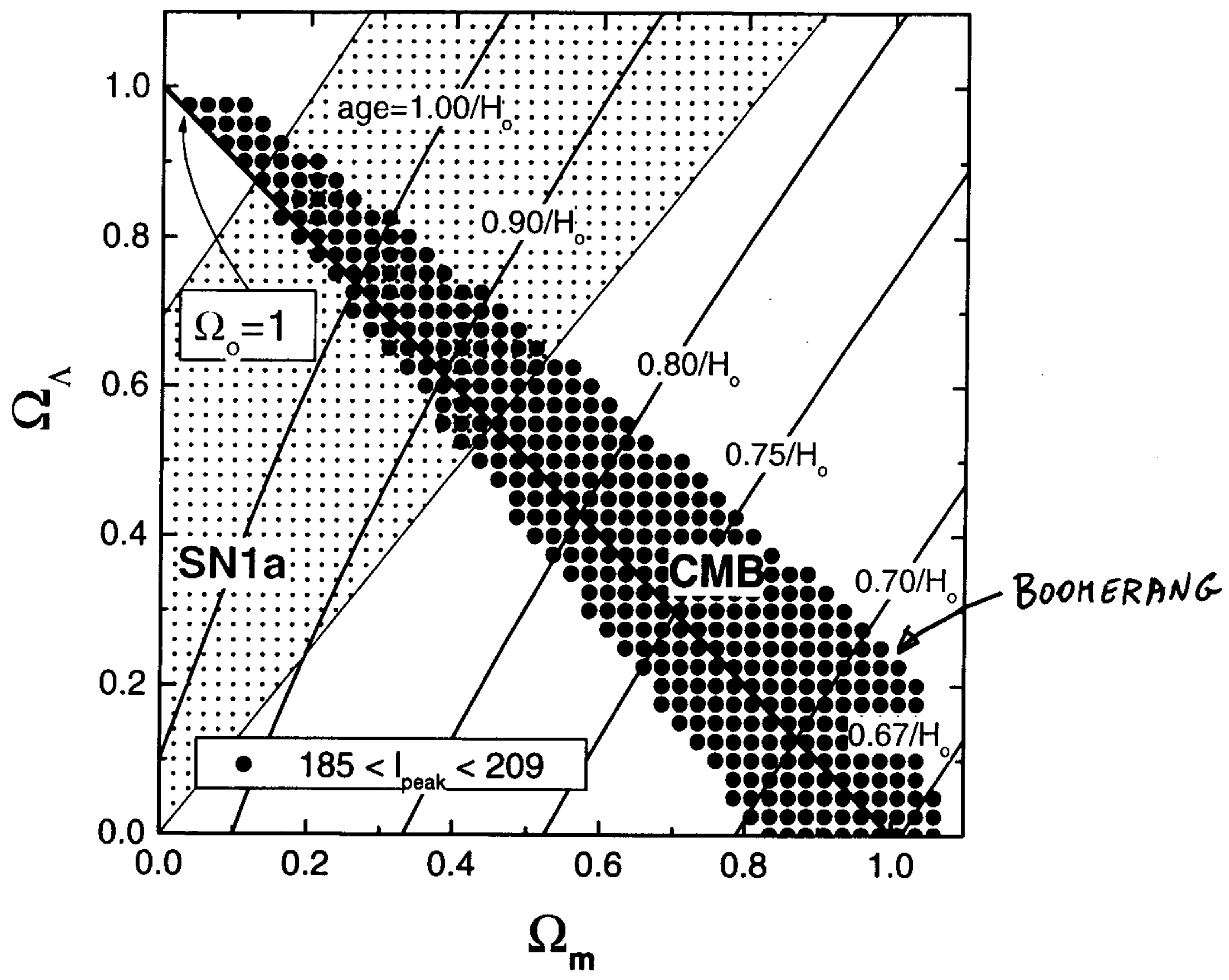


Figure 6. Constraints to Ω_M and Ω_Λ from CBR anisotropy, SNeIa, and measurements of clustered matter. Lines of constant Ω_0 are diagonal, with a flat Universe shown by the broken line. The concordance region is shown in bold: $\Omega_M \sim 1/3$, $\Omega_\Lambda \sim 2/3$, and $\Omega_0 \sim 1$. (Particle physicists who rotate the figure by 90° will recognize the similarity to the convergence of the gauge coupling constants.)

CONCORDANCE REGION

$$\Omega_M \simeq \frac{1}{3} \quad \Omega_\Lambda \simeq \frac{2}{3}$$



age=1.00/H_o
0.90/H_o
0.80/H_o
0.75/H_o
0.70/H_o
0.67/H_o
Ω_o=1
SN1a
CMB
BOOMERANG
185 < l_peak < 209
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0

WHAT IS THE DM MADE OF ?

Ω — Ω_{MATTER} at least 0.3
 — 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 γ, ν, baryons $\Omega_{SM} < 0.1$

$\Omega_B < 0.1$

$\Downarrow$

NON-BARYONIC DM
CALLS FOR NEW PHYSICS
BEYOND SM

DM RELIC PARTICLES

THERMAL — NON-THERMAL (ex. axions)

THERMAL → HOT, COLD

ex.: $m_\nu \sim 10\,eV$
$T^\nu_{decoupl} \sim MeV$

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

STANDARD MODEL AND DARK MATTER

SM: ONLY RELICS FROM THE EARLY UNIVERSE

$\gamma \to$ **CBR** $\quad T_\gamma \sim 2.7\ K$

$\nu \to$ **CBν** slightly less than
$m_\nu = 0$ $\quad \gamma$ CBR - a bit colder than γ

BARYONS $\to \Omega_B < 10\%$

➡ 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.

STRUCTURE FORMATION

DM

SEED OF DENSITY FLUCTUATIONS

AMOUNT AND NATURE OF THE MATERIAL IN THE UNIVERSE

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

COLD, HOT, WARM

INITIAL SPECTRUM OF ρ FLUCTUATIONS

$\Downarrow$

INFLATION OR TOPOLOGICAL DEFEC

→ SCALE INVAR. FLUCTUATION SPECTRUM

$\Downarrow$

EVOLUTION UNDER GRAVITY

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

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

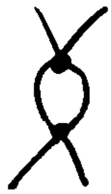
THEORETICAL REAPPRAISAL OF THE SM

a) intrinsic inconsistencies

ex: Fermi theory

→ four-fermion contact interaction

 $\sigma \sim G^2 s$ → violation of unitarity

 uncontrollable explosion of ultraviolet diverge
(non-renormalizability)

⇒ WE ARE NOT FORCED TO GO BEYOND THE S
BY THIS KIND OF INCONSISTENCIES

b) Questions that we think a fundamental theory should answer, but which do not find any satisfactory answer in the SM

- NO TRUE UNIFICATION

($G_F, e \leftrightarrow g_1, g_2$; g_1, g_2, g_3 ;
classically no explanation for charge quantization (why $|Q_d| = |Q_e|/3$?)
(30) → ANOM. CANCELL. (including gauge-grav. anom) charge qu

- gravity absent

- apart from g_1, g_2, g_3

$\Rightarrow$ LARGE NUMBER OF FREE PARAMETERS

Fermion spectrum
- why and how many fermion families
- fermion masses within the same generation (m_t/m_b ?) or between two different generations (m_μ/m_e ?)

Fermion mixing $\Rightarrow$ parameters of the CKM matrix

Arbitrariness in the scalar (higgs) sector
- how many and in which representations
- μ, λ param. in the scalar potential

c) FINE-TUNINGS $\Rightarrow$ look at the SM as a low-en. effective theory $\Longrightarrow$

OUT OF THE THREE CLASSES OF THEORETICAL ARGUMENTS PUSHING US BEYOND THE SM

- FLAVOUR PROBLEM (fermion masses and mixings)
- UNIFICATION OF FUNDAMENTAL INTER. (including gravity)
- GAUGE HIERARCHY PROBLEM

ONLY THE HIERARCHY ISSUE CALLS FOR NEW PHYSICS AT A SCALE CLOSE TO THE ELW. SCALE

1. THE STANDARD MODEL: A CRITICAL REAPPRAISAL

- SPONT. BROKEN GAUGE THEORY
  $\Downarrow$
  RENORMALIZABILITY

- EXTRAORDINARY **EXPER. SUCCESS**

- $\boxed{\text{"UNIFICATION" OF ELM. + WEAK}}$ (1)

- GIM, FCNC SUPPRESSION
- CP $\not{}$ (2)
- B and L **automatic** conservation at the perturbative level

- economy in the Higgs sector (1 doublet → M_W, M_Z, m_f) (3)

(1) – **LACK OF "TRUE" UNIFICATION**

a) no Q quantization

b) elm-weak $G_F, e \Rightarrow g, g'$

c) g_s, g, g' far apart

d) no gravity

(2) **FLAVOUR PROBLEM**

a) # of families

b) fermion masses

c) ν mass

d) CKM parameters

(3) **SCALAR PROBLEM**

a) arbitrariness in the scalar sector

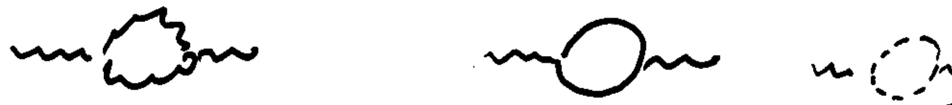
b) gauge hierarchy (G_F, M_{PL})

HOW WEAK and STRONG CAN MERGE TOGETHER

RGE :

Georgi, Quinn, Weinberg

$$\frac{d\alpha_i}{d\ln q^2} = b_i\, \alpha_i^2 + O(\alpha_i^3)$$



$$b_i = -\frac{1}{4\pi}\left[\frac{11}{3} C_2(G_i) - \sum_f \frac{4}{3} T(R)_f + \underset{\text{contr.}}{\text{scal.}}\right]$$

$C_2(G_i)$ = eigenvalue of the Casimir oper. of G_i

$$T(R) = \frac{d(R)\, C_2(R)}{r}$$

r # generators

$C_2(R)$ Casimir for repres. R

$SU(N)$: $T(N) = 1/2$

$$\begin{cases} b_3 = -(4\pi)^{-1}\left[\frac{11}{3}\times 3 - \frac{4}{3} n_{gener}\right] \\ b_2 = -(4\pi)^{-1}\left[\frac{11}{3}\times 2 - 4/3\, n_{gener}\right] \\ b_1 = -(4\pi)^{-1}\left[\ 0 - 20/9\, n_{gener}\right] \end{cases}$$

3 equations

Inputs: α_{em}, α_3 (at low energy)

Unknowns: M_X scale at which $\alpha_1 = \alpha_2 = \alpha_3$

α_G common value of $\alpha_1, \alpha_2, \alpha_3$ at M_X

$\sin^2\theta_W$ (from α_1, α_2
input α_{em}
unknown $\sin^2\theta$)

$\Rightarrow$ IT IS POSSIBLE TO

PREDICT a LOW EN.

(testable) fundamental quantity !

(exercise: solve the 3 eqs.)

$$M_X \sim 10^{15}\ \text{GeV}$$

$$\sin^2\theta_W \sim 0.2$$ ↑ further de

approximations:

1) RGE at 1 loop (today available at 2 loops)

2) **STEP APPROXIMATION**
(neglection of threshold effects → important when q^2 approaches M_X)

→ **GUT SCENARIO**

$E > M_X$	$E \sim M_X$	$M_W < E < M_X$	$E \sim M_W$
$G \supset \underbrace{SU(3)\times SU(2)\times U(1)}_{3\times 2\times 1}$	$G \to 3\times 2\times 1$	$3\times 2\times 1$	$3\times 2\times 1 \to 3\times 1_{em}$

GENERAL CONSEQUENCES OF A GUT SCHEME

* Q QUANTIZATION (Q generator of G)

* PREDICTION OF $\sin^2\theta_W$

* POSSIBLE FERMION MASS RELATIONS (f in a repres. of G)

* POSSIBLE B and L NON CONSERVATION (q and l in the same repres. of G)

* LARGE VALUE OF M_X

$$M_X \sim 10^{15}\ \text{GeV}$$

→ dim 6 operators responsible for proton decay ⇒ CLOSE TO EXP. LIMIT

$\sin^2\theta_W$

$e = g \sin\theta_W \Rightarrow \sin^2\theta_W = \frac{\alpha_{em}}{\alpha_2}$

correctly normalized Q : $\hat{Q}$

$\mathrm{Tr}\,\hat{Q}^2 = \mathrm{Tr}\,\hat{T}_3^2 \qquad \mathrm{Tr}\,\hat{T}_3^2\Big|_{\bar{5}} = 1/2$

$$Q \to \begin{pmatrix} 1/3 & & & & \\ & 1/3 & & & \\ & & 1/3 & & \\ & & & -1 & \\ & & & & 0 \end{pmatrix} \qquad \mathrm{Tr}\,Q^2 = 4/3 \qquad \hat{Q} = \sqrt{\frac{3}{8}}\,Q$$

$\hat{T}_3 = T \to \hat{g}_2 = g_2$

$\hat{e}\hat{Q} = eQ \Rightarrow \hat{e} = \sqrt{\frac{8}{3}}\,e$

$\sin^2\theta_W = \frac{e^2}{g^2} = \frac{3}{8}\frac{\hat{e}^2}{\hat{g}_2^2} = \frac{3}{8}$ at M_U where $\hat{e} = \hat{g}_2 = g_{un.}$

$\sin^2\theta_W$ is running $\Rightarrow$ renormalization of $\sin^2\theta_W$ from M_U to M_W

$\Rightarrow \sin^2\theta_W^{\overline{MS}}(m_Z) = 0.214\,^{+0.004}_{-0.003}$ problem for GUT's

$\Rightarrow \sin^2\theta_W^{exp} = 0.23155 \pm 0.0.0019$

+ proton decay problem in minimal ($SU(5)$) GUT

$\tau^p_{SU(5)} \lesssim 10^{32}$ yrs $\qquad \tau^p_{exp} > 10^{33}$ yrs

Courtesy of prof. Nishikawa

Summary of Nucleon Decay Searches

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \to e^+ + \pi^0$	52	44	0	0.2	33
$p \to \mu^+ + \pi^0$	52	35	0	0.1	27
$p \to e^+ + \eta$	45	17	0	0.3	11
$p \to \mu^+ + \eta$	45	12	0	0	7.8
$n \to \overline{\nu} + \eta$	45	21	5	9	5.6
$p \to \overline{\nu} + K^+$	33				7.3
$K^+ \to \nu\mu^+$ (spectrum)		40	–	–	3.3
prompt $\gamma + \mu^+$		4.4	0	0.4	2.1
$K^+ \to \pi^+\pi^0$		6.5	0	0.7	3.1
$n \to \overline{\nu} + K^0$	52				1.8
$K^0 \to \pi^0\pi^0$					
2-ring		3.2	9	8.0	0.64
3-ring		4.9	9	9.5	1.1
4-ring		1.7	1	3.3	0.84
$K^0 \to \pi^+\pi^-$		4.1	4	1.6	0.89
$p \to e^+ + K^0$	52	10.9	1	1.53	6.1
$p \to \mu^+ + K^0$	52				10
$K^0 \to \pi^0\pi^0$		6.1	0	0.7	4.6
$K^0 \to \pi^+\pi^-$					
2-ring		5.0	0	1.8	3.8
3-ring		3.1	0	0.4	2.4

∴ SEEKING PHYSICS BEYOND THE SM

SM → EFFECTIVE FIELD THEORY VALID UP TO THE CUTOFF SCALE Λ

SM field content: ϕ ψ $F_{\mu\nu}$
scalar fermion gauge fields

B, L (L_e, L_μ, L_τ) automatically conserved	Λ^4	dim 0 → cosm. const.
	$\Lambda^2 \phi^2$	dim 2 → scalar mass
No TREE LEVEL <u>FCNC</u>, GIM suppression	$\cancel{\Lambda \bar\psi \psi}$	dim 3 → fermion mass (forbidden by chirality)
↑ RENORM. OPERATORS	$(D\phi)^2$, $\bar\psi \not{D} \psi$, F^2, $\bar\psi \phi \psi$, ϕ^4	dim 4 → only log dependence on Λ
↓ NON-RENORM. OPER. B, L $\not=$ GIM NOT EFFECTIVE	$\frac{\bar\psi \psi \phi \phi}{\Lambda}$ $\frac{\bar\psi \psi \bar\psi \psi}{\Lambda^2}$ ϕ^6/Λ^2	dim 5, 6, ... → expansion in Λ^{-n}

$\Lambda \gg$ FERMI SCALE

SUPPRESSION OF OPER. OF DIM > 4

$B\!\!\!/$, $L\!\!\!/$, FCNC UNDER CONTROL

PROBLEM: $a\Lambda^2\phi^2$

need a extremely tiny

GAUGE HIERARCHY PROBLEM

$m_{HIGGS} > 130$ GeV

→ SCALARS TEND TO GET THE LARGEST AVAILABLE MASS SCALE IN THE THEORY

$\Lambda \sim$ FERMI SCALE

NO PROBLEM WITH $a\Lambda^2\phi^2$

→ a of $O(1)$

PROBLEM:

POTENTIALLY LARGE $B\!\!\!/$, $L\!\!\!/$, FCNC

CANDIDATE MSSM

$m_{HIGGS} < 130$ GeV

WHAT IF $\Lambda \gg M_W$?

GOOD POINT: ALL NON-RENORM. OPER. (creating troubles for p-decay, FCNC, ...) ARE LARGELY SUPPRESSED BY Λ^{-n}

BAD POINT (HIERARCHY PROBLEM)

$$m_H^2 \Rightarrow \Lambda^2 \gg v^2$$

$\hookrightarrow$ VEV which breaks $SU(2)\times U(1)$

but from $V = +\mu^2 \varphi\varphi^+ + \lambda(\varphi\varphi^+)^2$

$$\Rightarrow v = \sqrt{-\frac{\mu^2}{2\lambda}} \qquad m_{H_0}^2 \Rightarrow \lambda v^2$$

$$m_H^2 \sim \underbrace{\lambda v^2 + \textstyle\sum_i a_i}\Lambda^2 \qquad \sum_i a_i \sim v^2/\Lambda^2$$

FINE TUNING

NEED AN INCREDIBLE CONSPIRACY OF LOW- AND HIGH-ENERGY PHYSICS

HOW TO DEAL WITH THE SCALAR MASS PROBLEM

GET RID OF THEM

FORCE THEM TO RESPECT $m_H^2 \sim G_F^{-1}$

CONSTRUCTION OF GAUGE THEORIES WITHOUT (ELEMENTARY) SCALARS

$\Downarrow$

ex. $SU(2)_L \times U(1)$ without φ

$\langle \bar{u}_L u_R \rangle$ $\langle \bar{d}_L d_R \rangle \neq 0$

break $SU(2) \times U(1)$

scale $\sim f_\pi$ $\begin{cases} M_W \sim f_\pi \\ \pi \text{ eaten up by } W \end{cases}$

$\Downarrow$

try scaled up version of QCD with

$\langle \bar{U}_L U_R \rangle \Rightarrow F_\pi \sim 10^3 f_\pi$

"INDUCED" PROTECTION ON SCALAR MASSES

$\downarrow$

m_φ^2 not protected

m_ψ protected

$\downarrow$

put $\begin{pmatrix} \varphi \\ \psi \end{pmatrix}$ in a multiplet of a symm.

as long as this symm. is unbroken

$m_\varphi = m_\psi$

$\Rightarrow$ if this symm. broken $\sim M_W$

$m_\varphi - m_\psi \leq O(M_W)$

SM

FUND. SCALARS
UNIF. OF INTER.

NO FUND. SCALARS

GUT's $(\not B, \not L)$

SUSY AT LOW ENERGY (NEW PHYSICS AT THE TEV SCALE)

LOCAL SUSY (SUPERGRAVITY)

SUPERSTRINGS (consistent way of incorporating gravity with unified gauge theories)

DYNAMICAL BREAKING OF THE ELW. SYMM.

only scalars not fundam.

TECHNICOLOUR schemes

Extended TC to provide fermion masses

problems: FCNC, elw. precision tests

ALTERNATIVE $t\bar{t}$ CONDENSATE

Problem: m_t too large

also ferm. not fund.

COMPOSITE MODELS

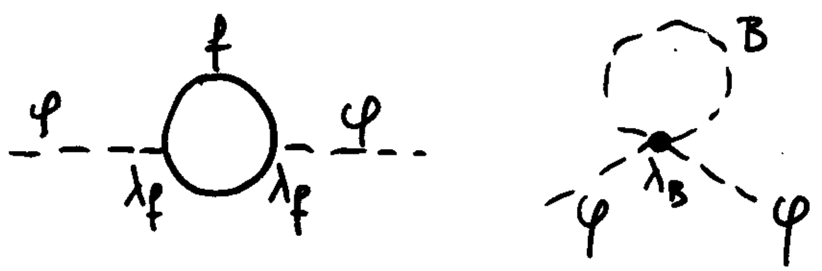
PROBL: no light on fermion spectrum

• HIERARCHY PROBLEM

$\Rightarrow$ SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1 TeV

$$m_\varphi^2 \propto \Lambda^2$$

$\Lambda \hookrightarrow$ scale of susy breaking



$$\delta m_\varphi^2 \sim \frac{\lambda_B - \lambda_f^2}{16\pi^2}\Lambda^2$$

$$\Rightarrow |m_B^2 - m_f^2|^{1/2} \sim \frac{1}{\sqrt{G_F}}$$

$\begin{pmatrix} B \\ F \end{pmatrix}$ in SUSY multiplet

2. WHAT IS SUSY

The simplest graded Lie algebra which is a symmetry of an S-matrix consistent with a relativistic quantum field theory involves the generators of the Poincaré group (even part of the algebra) as well as two anticommuting spinor generators of supersymmetry

$$[P^m, P^n] = 0$$

$$\boxed{\{Q^\alpha, \bar{Q}_{\dot\alpha}\} = 2\sigma^m_{\alpha\dot\alpha} P_m}$$

$$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$$

$$[Q_\alpha, P^m] = [\bar{Q}_{\dot\alpha}, P^m] = 0$$

$$[M^{mn}, P^q] = -i\left(P^m \eta^{nq} - P^n \eta^{mq}\right)$$

$$[M^{mn}, M^{qr}] = i\left(\eta^{mq} M^{nr} - \eta^{mr} M^{nq} + \eta^{nr} M^{mq} - \eta^{nq} M^{mr}\right)$$

$$\boxed{[M^{mn}, Q_\alpha] = -i\, \sigma^{mn\ \beta}_{\ \ \alpha}\, Q_\beta} \Longleftarrow \text{Q rotates as a spinor}$$

$$[M^{mn}, \bar{Q}^{\dot\alpha}] = -i\, \bar\sigma^{mn\dot\alpha}{}_{\dot\beta}\, \bar{Q}^{\dot\beta}$$

$$\left(\sigma^{mn\ \beta}_{\ \ \alpha} = \frac{1}{4}\left[\sigma^m_{\alpha\dot\alpha}\bar\sigma^{n\dot\alpha\beta} - \sigma^n_{\alpha\dot\alpha}\bar\sigma^{m\dot\alpha\beta}\right]\right.$$

$$\bar\sigma^{mn\dot\alpha}{}_{\dot\beta} = \frac{1}{4}\left[\bar\sigma^{m\dot\alpha\alpha}\sigma^n_{\alpha\dot\beta} - \bar\sigma^{n\dot\alpha\alpha}\sigma^m_{\alpha\dot\beta}\right]$$

spinor representation of generators of the Lorentz group).

Q_α, $\bar{Q}^{\dot\alpha}$ are generators of SUSY transf. and form the grading representation of the Poincaré algebra.

SUSY EXTENSION OF THE SM

$$V = -\mu^2 H^2 + \lambda H^4$$

$\mu \hookrightarrow M_W$

Λ SCALE >> ELW. SCALE

ELW. SCALE $10^2 - 10^3$ GeV

ex: GUT scale $\sim 10^{15}$ GeV

Energy

SM $\longrightarrow$ Λ

$\Lambda \hookrightarrow$ scale at which new physics sets in

$\Rightarrow \Lambda^2 H^2$ no symm. protection

fermion masses

gauge bosons masses

< $\boxed{\text{ELW. SYMM. BREAKING}}$

$\Downarrow$

m_f, m_W CANNOT JUMP TO Λ

$H \longleftrightarrow \psi \rightarrow$ mass protecti:

$\Downarrow$

SUSY

new symm. : changing the spin of particles in its repres.

SUSY : good symm. down to the elw. scale

$\boxed{\text{LOW ENERGY SUSY}} \Rightarrow m_{s\text{-particles}} \lesssim O(1\,\text{TeV})$

THE SUPERSYMMETRIC STANDARD MODEL

Particle content

VECTOR MULTIPLETS

$J=1$		$J=1/2$	
g (gluon)	$\longrightarrow$	$\tilde{g}$	(gluinos)
$W^{\pm}, W^3$	$\longrightarrow$	$\tilde{W}^{\pm}, \tilde{W}^3$	(winos)
B	$\longrightarrow$	$\tilde{B}$	(bino)

CHIRAL MULTIPLETS

$J=1/2$		$J=0$	
q_L, q_R (quarks)	$\longrightarrow$	$\tilde{q}_L, \tilde{q}_R$	(squarks)
l_L, l_R (leptons)	$\longrightarrow$	$\tilde{l}_L, \tilde{l}_R$	(sleptons)
([illegible]) $\tilde{H}_1, \tilde{H}_2$	$\longrightarrow$	H_1, H_2	(higgses)

$\hookrightarrow$ 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

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

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

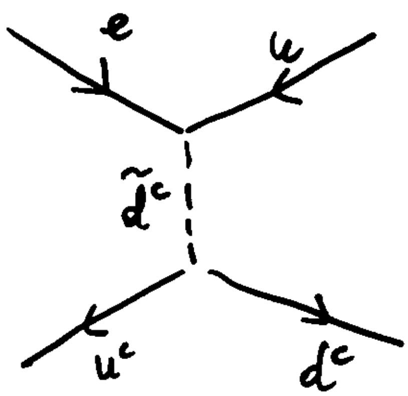
$$\lambda' \, L \, Q \, d^c|_{\theta\theta} \Rightarrow L \neq 0$$

dim 4 operators violating either B or L

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

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

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

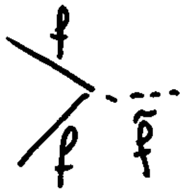


$p \to e^+ + X$

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

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

R PARITY

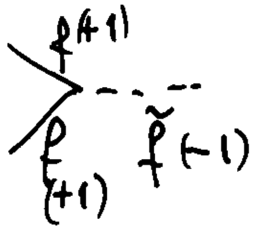


all $\lambda, \lambda', \lambda''$ dangereous vertices involve two (ordinary) fermions and one (supersymmetric) sfermion

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

and R (susy particles) $= -1$

$\Rightarrow$



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Gauge $\otimes$ N=1 susy $\otimes$ 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

IMPLICATIONS OF R-PARITY

SUSY PARTICLES CAN BE CREATED OR DESTROYED ONLY IN PAIRS

THE LIGHTEST SUSY PARTICLE (LSP) IS ABSOLUTELY STABLE

(relic candidate)