UNIFICATION OF FORCES AND THE EVOLUTION OF THE UNIVERSE

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I. Introduction

Starting With Maxwell's Unification of Electricity & Magnetism, the quest for unification of fundamental particles & their forces has progressed remarkably well over the last four decades Through an interplay

Between Theory & Experiments

↓

Probing BOTH into the World of the

VERY SMALL & of The VERY LARGE

$10^{-16} \rightarrow 10^{-32}$ cm 10^{+28} cm

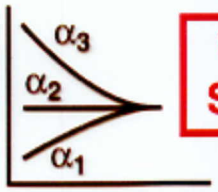
A PREVIEW → Chart 1

VERY SMALL

10^{-16}cm to 10^{-30}cm

EW UNIF ⊕ QCD → Grand Unification

Standard Model ~100 GeV

1. Spectrum of (q, ℓ)
2. Quantize Q_{em}
3. 

With SUSY
4. "m(ν_3)" ~1/20 eV
5. $(n_{b/s})_{Theor} \sim 10^{-10}$-$10^{-11}$
6. SUSY LSP or Axion as CDM

VERY LARGE

10^{28}cm

Stand. Big Bang Model ⊕ Inflation

$T \sim 10^{16}$ - 10^{14} GeV; $t \sim 10^{-38}$-10^{-34} sec

$T_{rh} \sim 10^{9}$-10^{6} GeV

1. Gross Homog/Isotropy
2. Flatness: $\Omega_{Tot}^{obs} = \Omega_M + \Omega_\Lambda = 1.01 \pm 0.01$
3. $\delta\rho/\rho \sim \delta T/T \sim 10^{-5}$
4. $(n_{b/s})^{obs} \approx 10^{-10}$
5. Dark Matter: $\Omega_{CDM} \approx 0.23$; $\Omega_B \approx 0.04$
6. • Galaxy Formation
   • Stars Born / Shine / Die
7. Evolution of Life!
8. Dark Energy $\Omega_\Lambda^{obs} = 0.73$

A Total Mystery

10^{-32}cm

String/M Theory

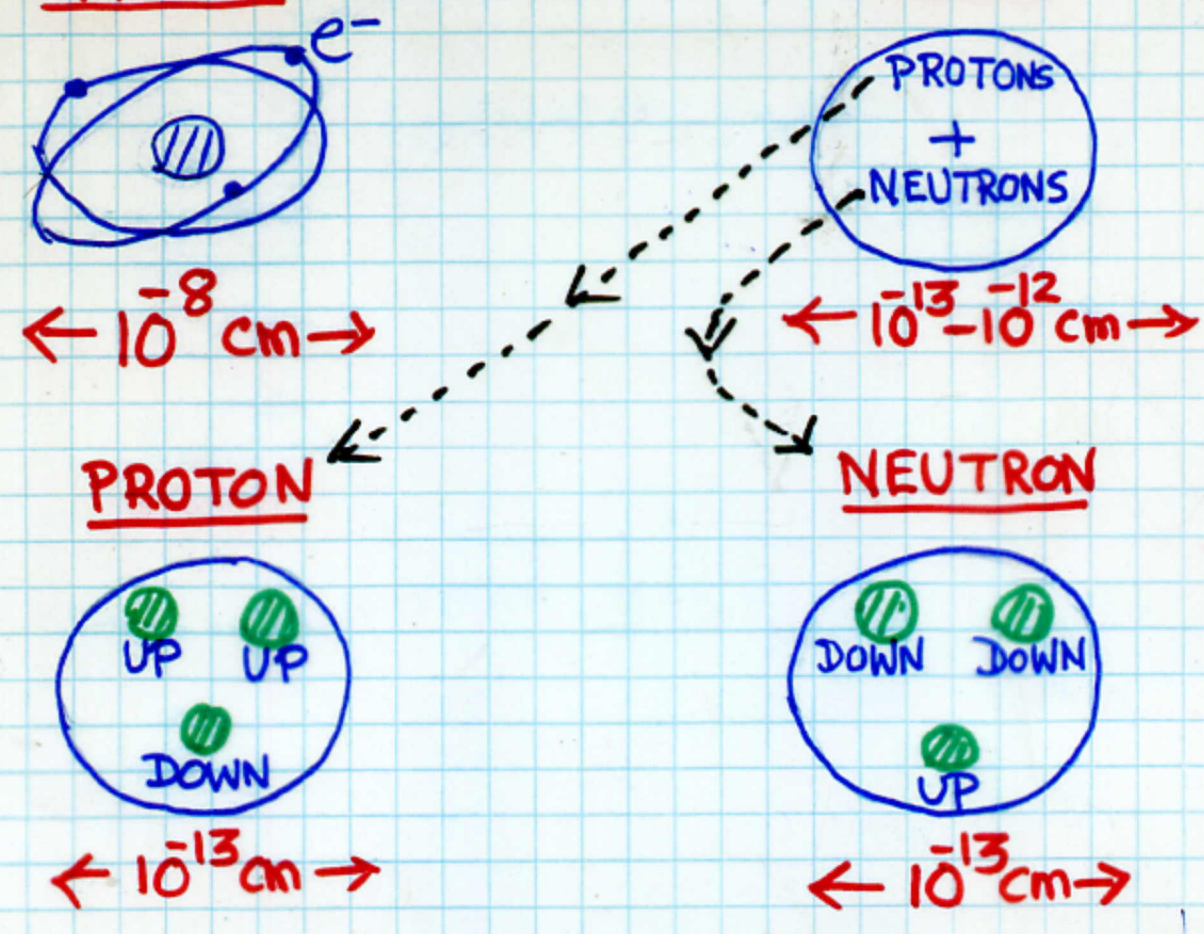
dim. d = 10/11

Scope for a Truly Unified Theory with Good Quantum Gravity

Still Evolving

7-2006
8733A2

II Building Blocks: The Fundamental Particles



	Spin	Charge	Size
up quark (u)	½	+⅔ |e|	$< 10^{-17}$ cm
Down Quark (d)	½	−⅓ |e|	$< 10^{-17}$ cm

PROTON = uud

NEUTRON = ddu

ALL "STABLE" MATTER MADE OF JUST 3 OBJECTS → up quark (u), down quark (d), electron (e^-)

2(b) Three Families of Quarks and Leptons

Publication of Forces. Modified on Jan 31, 2013 at 13:53:53.

QUARKS		Charge	Mass	LEPTONS	Mass
$\begin{pmatrix} u \\ d \end{pmatrix}$	up down	+2/3 −1/3	3 MeV 6 MeV	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	< 2 ev 0.5 MeV
$\begin{pmatrix} c \\ s \end{pmatrix}$	charm strange	+2/3 −1/3	1300 MeV 110 MeV	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	< 2 ev 6 MeV
$\begin{pmatrix} t \\ b \end{pmatrix}$	top bottom	+2/3 −1/3	170 GeV 4.4 GeV	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$	< 2 ev 1.8 GeV

1) Why 3 Families? Why Nature Replicates?

2) Mass-Hierarchies (charged quarks and leptons)?

a) Inter-Family: $m_u : m_c : m_t \sim 10^{-5} : 10^{-2} : 1$

b) Intra-Family: $m_t : m_b : m_\tau \sim 10^{-2} : 1/40 : 1$

3) Neutrino Masses Way Out of Line

So So Light: $m(\nu_i) \neq 0$, But $\dfrac{m(\nu_\tau)}{m_{top}} \sim 10^{-12}$

Suggest New Physics Involved.

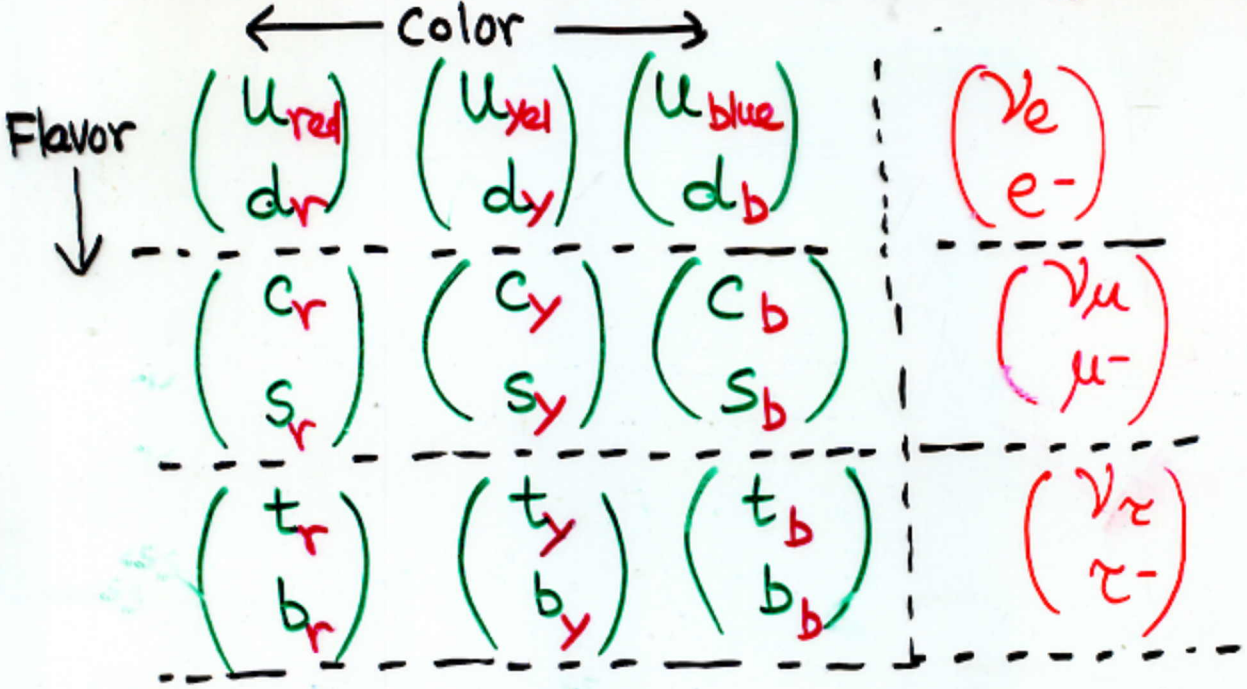
B. Quarks possess "Flavor" & "Color" charges

Quark-picture incompatible with Pauli Principle unless assume each quark comes in 3 types ↔ "colors"

$N^{*++}_{\text{spin } 3/2}(1238\,\text{MeV}) = (u\uparrow\, u\uparrow\, u\uparrow) \leftrightarrow \varepsilon_{\alpha\beta\gamma} u_\alpha u_\beta u_\gamma$

Baryons $= \varepsilon_{\alpha\beta\gamma} q_\alpha q_\beta q_\gamma$; Mesons $= \sum_{\alpha = \text{red, yel, blue}} q_\alpha \bar{q}_\alpha$

They are Color "neutral" ↔ Singlets of SU(3)-Color



$m(u_{red}) = m(u_{yel}) = m(u_{blue})$;
$Q(u_{red}) = Q(u_{yel}) = Q(u_{blue}) = \frac{2}{3}|e|$

Color degree of freedom turned out to be essential to generate satisfactory quark-quark force & thereby nuclear force (p, n)

C. The Four Basic Forces

Force	Acts on	Messengers (quanta)	Strength "$g^2/4\pi$"	Range
Strong	• (p, n) → Nuclear Force • q-q Force	Pions (π) Gluons (8)	O(1) —	10^{-13} cm. —
ELECTRO MAGNETIC	e-e, e-p	Photon (γ)	1/137	Infinite
WEAK RADIO-ACTIVE	• $n \to p\, e^- \bar{\nu}_e$ • $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ • $c \to s\, e^+ \nu_e$	$W^\pm$	10^{-5}	10^{-16} cm
	• $\nu_\mu e^- \to \nu_\mu e^-$	Z^0	10^{-5}	10^{-16} cm
(*) Gravity	Mass & Energy	Graviton	• 10^{-39}	Infinite

(*) Superstrong Near Blackholes

All Four Forces crucial To The Cosmic Drama

→ Evolution of The Universe From Big Bang to Now / Origin of Life.

→ Even Neutrinos - Almost massless & Electrically neutral, with only Weak & Gravit. Forces - play such crucial roles.

→ **Pre-designed ?**

IV Steps in the Unification Ladder

S-1) Maxwell $\vec{E} \longleftrightarrow \vec{B}$ (Late 19th Century

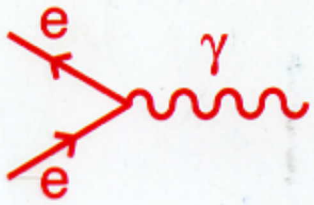
S-2&3) Relativity & QM (2 Big Steps)

S-4) General Relativity (1915)

S-5) Relativistic QFT (1929-1950)

$$\mathcal{L}_{em} = e\, j^{\mu}_{em}(x)\, A_{\mu}(x)$$

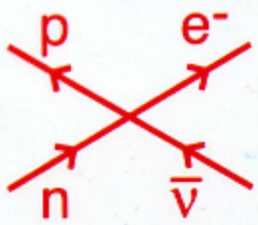
$$= e\, [\bar{\psi}_e(x)\gamma^{\mu}\psi_e(x)]A_{\mu}(x)$$



(i) Particle Creation/Annihilation

e.g. $\mathcal{L}_{weak} = G_F(\bar{p}(x)\Gamma^{\mu}n(x))(e(x)\Gamma_{\mu}\nu(x))$

$n \rightarrow p e^{-} \bar{\nu}$



(ii) Matter $\longleftrightarrow$ Anti-matter (Dirac)

$e^{-} \longleftrightarrow e^{+}$

$p \longleftrightarrow \bar{p}$

$n \longleftrightarrow \bar{n}$

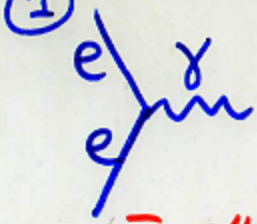
$\nu \longleftrightarrow \bar{\nu}$

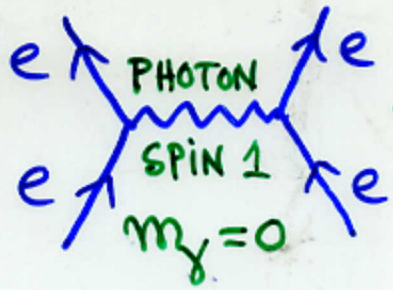
$$\frac{n_B - n_{\bar{B}}}{\eta_{\gamma}} \sim 10^{-10}$$

$e^{-}e^{+} \rightarrow$ Photons

$p\bar{p} \rightarrow$ Mesons

(iii) Quantum Origin of Forces: Messengers

① 

$e\,\bar{\psi}_e \gamma^\mu \psi_e A_\mu$ → 

→ Long Range

$V(r) = e^2/r$

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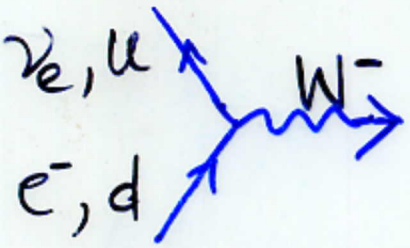
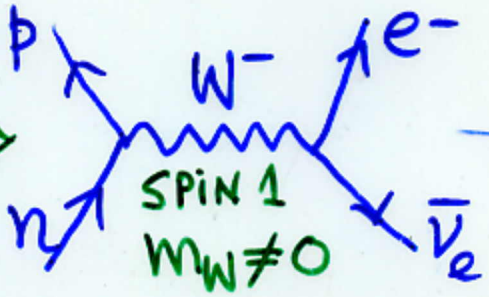
② THE WEAK FORCE $g_W J_\mu^{(W^+)} W_\mu^+ + hc$



→ 

→ Short Range Force

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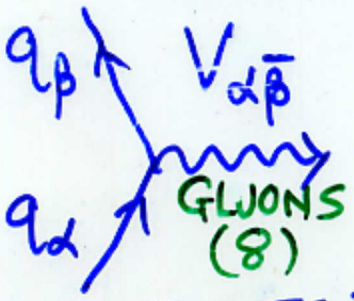
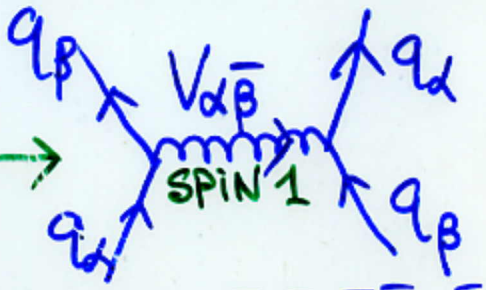
③ The STRONG q-q Force $g_s J_\mu^{\alpha\bar{\beta}} V_{\bar{\alpha}\beta}^\mu + hc$



→ 

→ NOVEL PROPERTIES

(1) ASYMP. FREE

(2) CONFINEMENT

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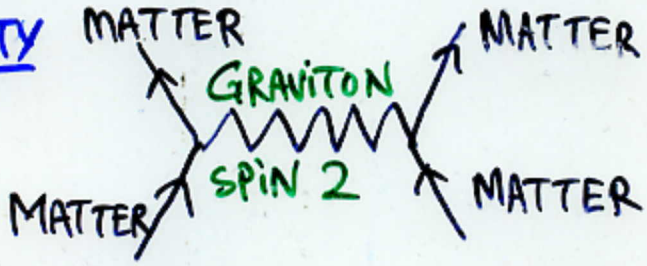
④ GRAVITY 

Long Range

$V(r) \propto 1/r$

$m_{graviton} = 0$

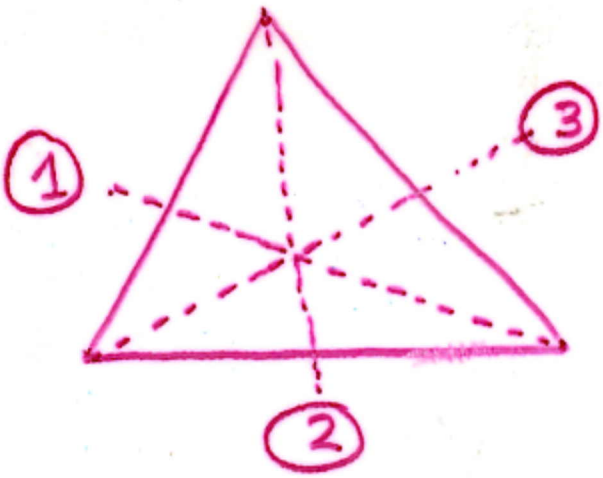
UNIFICATION OF FUNDAMENTAL PARICLES & FORCES

1) SYMMETRY IN THE LAWS OF NATURE

2) SPONTANEOUS BREAKING OF SYMMETRIES

Symmetries of Form

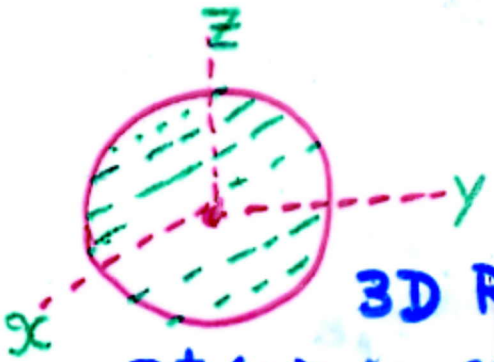
1)



2) Circle

2D - Rotation

3) Sphere



3D Rotation

$R^+(3) \leftrightarrow SU(2)$

Symmetries In The Laws of Nature

Symmetry	Conserved Entity
1) Space Translation: $\vec{x} \to \vec{x}' = \vec{x} + \vec{a}$	Momentum $\vec{p}$
2) Time Translation $t \to t' = t + t_0$	Energy E
3) 3D Rotation	Angular Mom. $\vec{J}$.

GAUGE SYMMETRY: A PRINCIPLE TO GENERATE FUNDAMENTAL INTERACTIONS

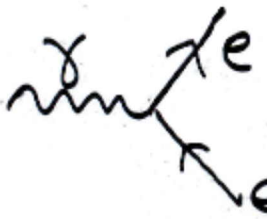
(1) QUANTUM ELECTRODYNAMICS (QED)

$$\mathcal{L}_{free} = \bar{\psi}_e(x)[i\gamma^\mu \partial_\mu - m]\psi_e(x) \quad \text{DIRAC}$$

Invariant under $\psi_e(x) \to e^{iQ_e\Lambda}\psi_e(x)$ if Λ = Const. But if demand Invariance with $\Lambda = \Lambda(x)$, Need to introduce a massless spin-1 Field $A_\mu(x)$ with $A_\mu(x) \to A_\mu(x) + \partial_\mu\Lambda(x)$ $\to$

$$\mathcal{L} = \bar{\psi}_e(x)[i\gamma^\mu(\partial_\mu - iQ_eA_\mu(x)) - m]\psi_e(x)$$

$$-\tfrac{1}{4}F_{\mu\nu}^2 + m_A^2 A^\mu A_\mu \quad (F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$$



$$Q_e\bar{\psi}_e(x)\gamma^\mu\psi_e(x)$$

→ A PRINCIPLE TO GENERATE FUND. INTERACTIONS

→ QED Extremely Successful

→ Anom mag. moment $(g-2)_e$ → Verified to 10th decimal place.

b) TRANSFORMING ONE FIELD TO ANOTHER

$$\psi_N = \begin{pmatrix} p(x) \\ n(x) \end{pmatrix} \rightarrow \left\{ \begin{matrix} p \leftrightarrow n \\ p \leftrightarrow p \\ n \leftrightarrow n \end{matrix} \right\}$$

→ YANG & MILLS → NON-ABELIAN SU(2) SYMMETRY

$$\psi_N \rightarrow \left[e^{ig \sum_{i=1}^{3} \tau^i/2 \cdot \Lambda^i(x)} \right] \psi_N(x)$$

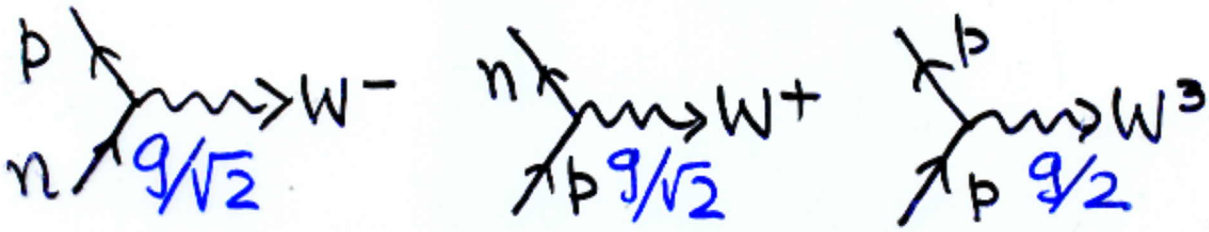
SU(2)

$\tau^i/2$ → 2×2 PAULI MATRICES

FOR GAUGE INVARIANCE NEED

3 MASSLESS SPIN 1 FIELDS → CAN BE MESSENGERS OF WEAK FORCE

W^+, W^-, W^3

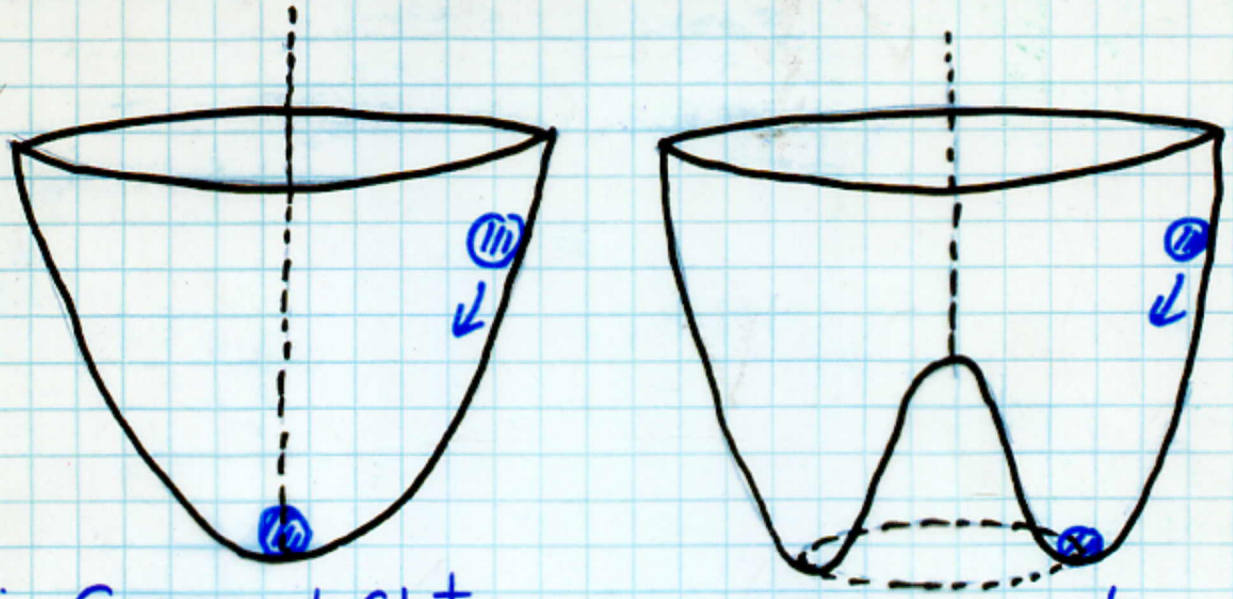


, ALSO

NON-ABELIAN

BUT HOW TO GIVE MASSES TO W's ?

S-8 Spontaneous Breaking of Symmetry: Higgs Mechanism



Ground State
Preserves Symmetry

Ground state
Breaks Symmetry

(Higgs / Englert & Brout / Kibble.. ← Anderson)

Even if symmetry exact in Basic Eqns,
Solutions need not preserve the Symmetry!

W^+, W^-, W^3 become massive through SSB

↓

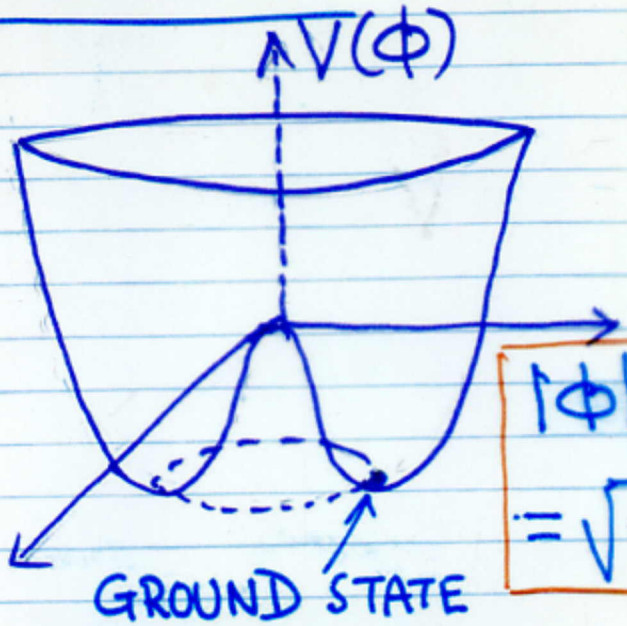
(1) Preserves Good Quantum Behaviour //
Renormalizable like QED — 't Hooft Veltman

(2) Opens The Door To Higher Unification

spin-0 Higgs Field $\phi(x)$

$$V(\phi) = \mu^2 \phi(x)\phi^*(x) + \lambda(\phi\phi^*)^2$$

$$\mu^2 < 0 \,, \lambda > 0$$



$$|\phi|_{\text{At Min.}} = \sqrt{-\mu^2/2\lambda} \neq 0$$

$$\langle \text{Ground state} | \phi | \text{Ground State} \rangle \neq 0$$

Short Hand $\langle 0 | \phi | 0 \rangle$ or $\langle \phi \rangle \neq 0$

VEV → Vacuum Exp. Value

$\langle \phi \rangle \neq 0 \rightarrow$ symmetry Spont'ly Broken

5-9 ELECTROWEAK UNIFICATION $(SU(2)_L \times U(1)_Y)$

Weinberg / Salam / Glashow (1961-68)

$$\psi^e = \left(\frac{1+\gamma_5}{2}\right)\psi^e + \left(\frac{1-\gamma_5}{2}\right)\psi^e$$

$$\equiv \psi^e_L + \psi^e_R$$

If $m_e = 0 \rightarrow$ (MOMENTUM ⟸ SPIN) LEFT CHIRAL ; (MOMENTUM ⟹ SPIN) RIGHT CHIRAL

$SU(2)_L \rightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, u_R, d_R, e_R, \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, NO ν_R

$Y \rightarrow \quad 1/3 \quad -1 \quad 4/3 \quad -2/3 \quad -2 \quad 1$

$SU(2)_L \times U(1)_Y \xrightarrow[\text{SSB}]{\langle\phi\rangle \sim 250\ \text{GeV}} U(1)_{em}$ → PHOTON

$(W^+, W^-, W^3)\ (B^0)$

W^+, W^- massive → Yet Theory Renormalizable

$$\begin{pmatrix} W^3 \\ B^0 \end{pmatrix} \rightarrow \begin{cases} Z^0 = \cos\theta\, W^3 + \sin\theta\, B^0 \rightarrow \text{Massive} \\ A = -\sin\theta\, W^3 + \cos\theta\, B^0 \rightarrow \text{Massless} \end{cases}$$

Predict $m_{W\pm} \simeq 80$ GeV , $m_Z \simeq 90$ GeV

MANY MORE // EXPECT HIGGS AT TEVATRON OR LHC

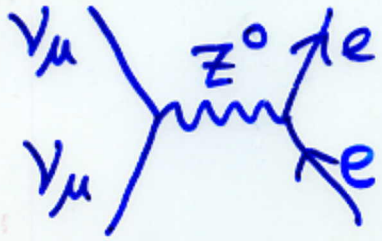
$SU(2)_L \times U(1)$

$$\text{PHOTON} = W_3 \cos\theta + B^0 \sin\theta$$
$$Z^0 = -W_3 \sin\theta + B^0 \cos\theta$$

PREDICT

① $m_{W^\pm} \simeq 80\ \text{GeV}$
$m_{Z^0} \simeq 90\ \text{GeV}$ } FOUND

② Host of NEUTRAL CURRENT INT



$\nu_\mu e \to \nu_\mu e$
$\nu p \to \nu p$, FOUND
$\bar{\nu} N \to \bar{\nu} N$
$ep \to ep$ (Parity Violation)

③ EXPECT HIGGS BOSON ~ 100 - 200 GeV
m_{H^0} AT TEVATRON OR
AT LEAST AT LHC!

③ Color Gauge Force: Origin of Strong Interaction

Need Color degree of freedom for quarks Greenberg/Han & Nambu 1964/65

$\pi^+ p \to \Delta^{++}(J=3/2^+) \to u\uparrow u\uparrow u\uparrow \to \varepsilon_{\alpha\beta\gamma} u_\alpha u_\beta u_\gamma$

$\longleftarrow$ SU(3)-Color $\longrightarrow$

$\begin{bmatrix} u_{red} & u_{yel} & u_{bl} \\ d_{red} & d_{yel} & d_{bl} \end{bmatrix}$

Nambu (65)
Superstrong Color Force
$\oplus$
Med. Strong (ρ, ω) Force
Fundamental

1972 $SU(2)_L \times U(1)_Y \times SU(3)^c$

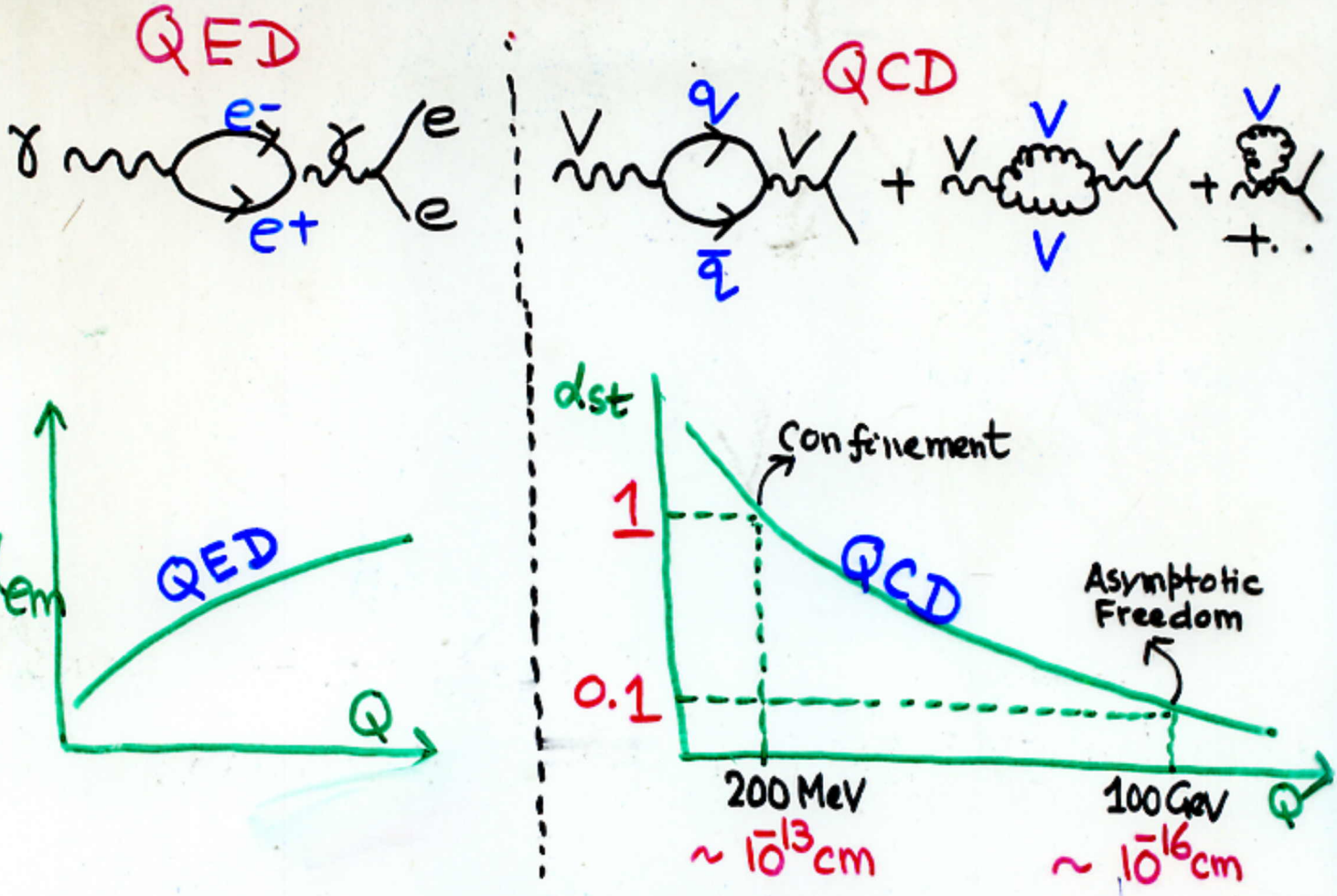
- The only way to generate strong Int. by a gauge principle, together with weak & EM int.
- SU(3) Color gauge force → The ONLY SOURCE of Fund. Strong Int → NNπ, NNρ, NNω are eff. int. (1972)
- Asymptotic Freedom: (Gross & Wilczek/Politzer → 1973)

$$q^u = \begin{pmatrix} q^u_{red} \\ q^u_{yel} \\ q^u_{bl} \end{pmatrix} \longrightarrow e^{i\vec{\lambda}/2 \cdot \vec{\Lambda}(x)} q^u(x)$$

$\Downarrow$

$SU(3)_f \Rightarrow 3^2 - 1 = \boxed{8}$ spin 1 gluons

(3B) SU(3) - Color Gauge Force – Novel Quantum Properties

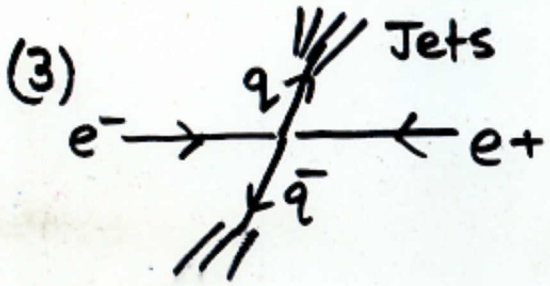


Remarkable agreement with Observations

(1) 

Structure Funcns (Q^2, ν) → SLAC Scaling & Deviations

(2) $R = \sigma(e^-e^+ \to \text{Hadrons}) / \sigma(e^-e^+ \to \mu^-\mu^+)$

(3) 

+ Other Tests

B) SM Now Brilliantly Successful

since 1972, both the $SU(2) \times U(1)$ EW Theory & QCD have been confirmed by numerous experiments

→ A Triumph of Gauge Principle & SSB

→ Waiting To see Higgs at LHC/Fermilab

But ∃ Clear Evidence For Physics Beyond SM

1) ν Masses ($\sqrt{\Delta m^2(\nu)_{23}} \sim 1/20\,eV$)

2) Higgs Mass Fine Tuning

3) Need For Inflation → Horizon, Flatness $\Omega = 1$

4) Dark Matter (Cold): $\Omega_{CDM} \approx 0.23$

5) Baryogenesis ↔ Leptogenesis

All Five Go Well With SUSY Grand Unification!

⇓

There exists PHYSICS BEYOND SM

6) Dark Energy: Cosm. Const. $\Omega_\Lambda \approx 0.72$ } A MYSTERY FOR ALL THEORIES

II) GRAND UNIFICATION: OVERVIEW

A) MOTIVATIONS (1972) → PURELY AESTHETIC

1. Remove arbitrariness in choice of SM Quantum Nos. (Y_W, $SU(2)_L$, $SU(3)_C$)
2. Quantization of Q_{em}
3. $\boxed{Q_{e^-} = -Q_p}$
4. Co-existence of q & l
5. Co-existence of (W, EM, strong) (g_1, g_2, g_3)

MAIN IDEA (1972-74)

1. Unify {q & l} → { one kind of Matter ↓ symmetry Group G
2. Unify {W, EM & strong} → { ASPECTS OF ONE FORCE ↓ Gauge symm. G

$$G \xrightarrow[SSB]{\langle \Sigma_i \rangle \sim M} SU(2)_L \times U(1)_Y \times SU(3)_C \xrightarrow[\sim 250\ GeV]{\langle \Phi_H \rangle} U(1)_{em} \times SU(3)_C$$

Distinctions between {q & l} & {W, EM & strong} forces → Low Energy Phenomena arising from SSB → To disappear at predictably high energies

↓

MANY TESTABLE PREDICTIONS

B) Alt. Routes To Grand Unification

$$G(213) = SU(2)_L \times U(1)_Y \times SU(3)^C$$

$$\begin{pmatrix} u_r & u_y & u_b \\ d_r & d_y & d_b \end{pmatrix}_L^{1/3}, \; (u_{r,y,b})_R^{4/3}, \; (d_{r,y,b})_R^{-2/3}, \; \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L^{-1}, \; (e^-_R)^{-2}$$

5 disconn. multiplets // Arb. Y_W, $SU(2)$, $SU(3)^C$ Q. Nos.

↓

1972 $G(224) = SU(2)_L \times SU(2)_R \times SU(4)^C_{L+R}$ (L+R)

$$F^e_{L,R} = \begin{bmatrix} u_r & u_y & u_b & \nu_e \\ d_r & d_y & d_b & e^- \end{bmatrix}_{L,R} \quad F^e_L = (2,1,4) \quad F^e_R = (1,2,4)$$

$$Q_{em} = I_{3L} + I_{3R} + \frac{B-L}{2}$$

Advantages of G(224)

- All 16 in one L-R Conj. multiplet // L-R Symm
- Explain Y_W & All Q. Nos. // Quantize Q_{em} //
- $Q_{e^-} = -Q_p$ // (ν_R // B-L) ← Need For seesaw & Leptogenesis

↓

SO(10): 16 (one coupling)

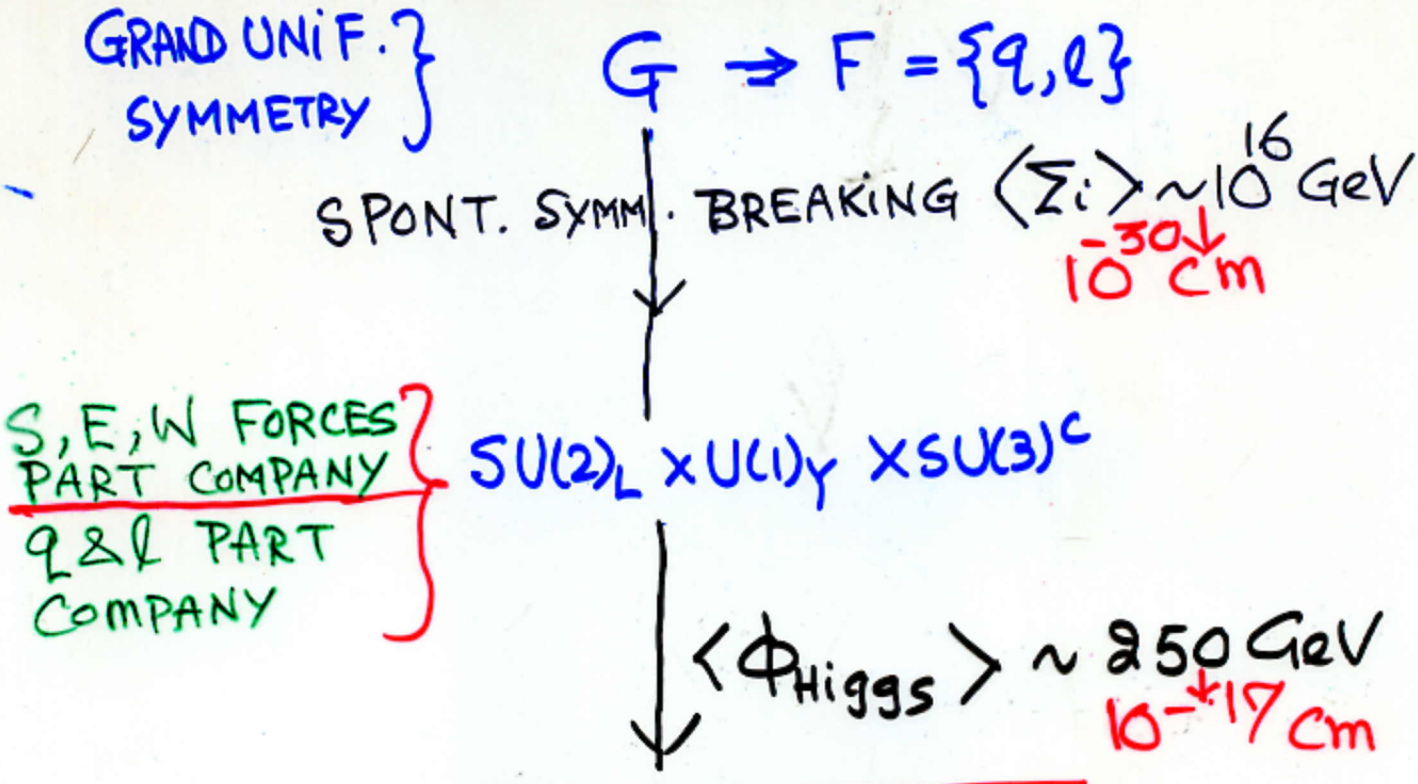
All Advantages of G(224) retained by SO(10), not SU(5)

SU(5): $\bar{5} + 10$ → Problem with ν Masses & Leptogenesis.

NO ν_R, NO B-L

V SOME PREDICTIONS OF GRAND UNIFICATION

Main IDEA



EVENTHOUGH GRAND UNIF SYMM. HOLDS AT VERY VERY HIGH ENERGIES ~ 10^{16} GeV, FORTUNATELY IT MAKES MANY PREDICTIONS THAT CAN BE TESTED AT LOW ENERGIES.

Four Striking Consequences of These Ideas

① Meeting of The Gauge Couplings

② $m_\nu \neq 0$ & m_ν small as observed

③ Proton Decay

With SUSY (d=5)

$p \to \bar{\nu} K^+$
$\to \bar{\nu} \pi^+$

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

$\Gamma^{-1}(p \to e^+ \pi^0) \approx 10^{35\pm1}$ yrs. (theory)

d=6 →

d=5 → $\Gamma^{-1}(p \to \bar{\nu} K^+)_{\text{SUSY SO(10) or SUSY G(224)}} \approx 10^{30}\text{-}10^{34}$ yrs.

④ A General Framework, especially with ν_R & B-L as above, For Matter-Antimatter Asymmetry.

(C) Supersymmetry

Golfand, Likhtman (71)
Wess, Zumino (74)

Fermions $\xleftrightarrow{Q}$ Bosons
Spin 1/2 Spin 0 or 1

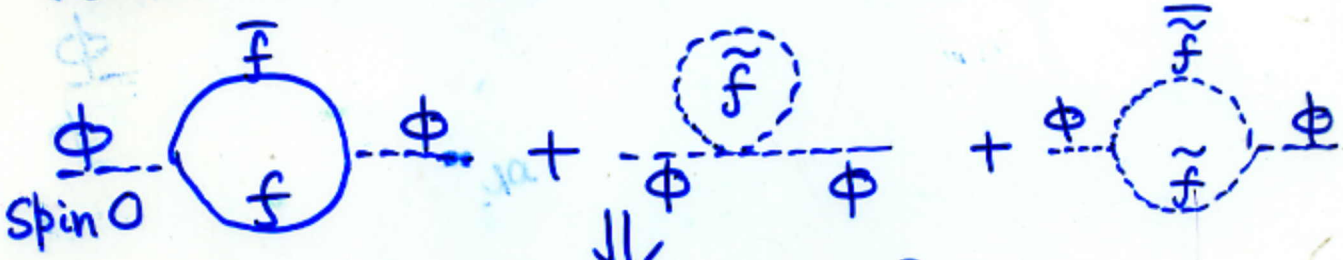
$$\{Q, \bar{Q}\} = 2\sigma^{\mu} P_{\mu}$$

$(\text{quark})_{1/2} \Longleftrightarrow \text{squark}\ (\tilde{q})_0$

$(\text{lepton})_{1/2} \Longleftrightarrow \text{slepton}\ (\tilde{l})_0$

$(\text{photon})_1 \Longleftrightarrow \text{photino}\ (\tilde{\gamma})_{1/2}$

Remarkable quantum Properties



$$\delta m^2_{\text{Higgs}} \sim \frac{\alpha_r}{\pi} \left| m_f^2 - m_{\tilde{f}}^2 \right|$$

Fermion Boson

Expect $\boxed{(m_{\tilde{q}}, m_{\tilde{l}}, m_{\tilde{g}}) \lesssim 1\,\text{TeV}}$ (LHC)

- Goes Well with Grand Unification //
- Needed by String Theory
- Lightest SUSY Particle → Candidate For Cold Dark Matter

D) EVIDENCE FOR GRAND UNIFICATION

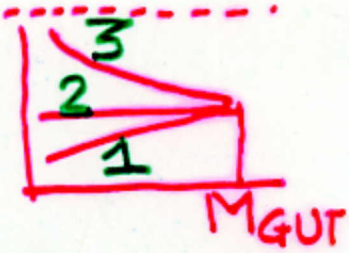
1) Family Structure - Quantum Nos.

2) Charge Quantization

3) $Q_{e^-} = -Q_p$

4) Meeting of the 3 gauge Couplings
SUSY Grand Unification

$M_{GUT} \simeq 2 \times 10^{16}$ GeV



5) $\sqrt{\Delta m^2(\nu)_{23}} \approx 1/20$ eV $\leftrightarrow$ SU(4)$_f \rightarrow \nu_R$ // B-L

$m(\nu^\tau)_{Dirac}$ //

$M_{GUT} \rightarrow$ Maj ν_R

Seesaw

6) $m_b(GUT) = m_\tau$

7) $m(\nu_\tau)_{Dirac} = m_{top}(GUT)$

$\rightarrow SU(4)^c$

SO(10) // G(224)

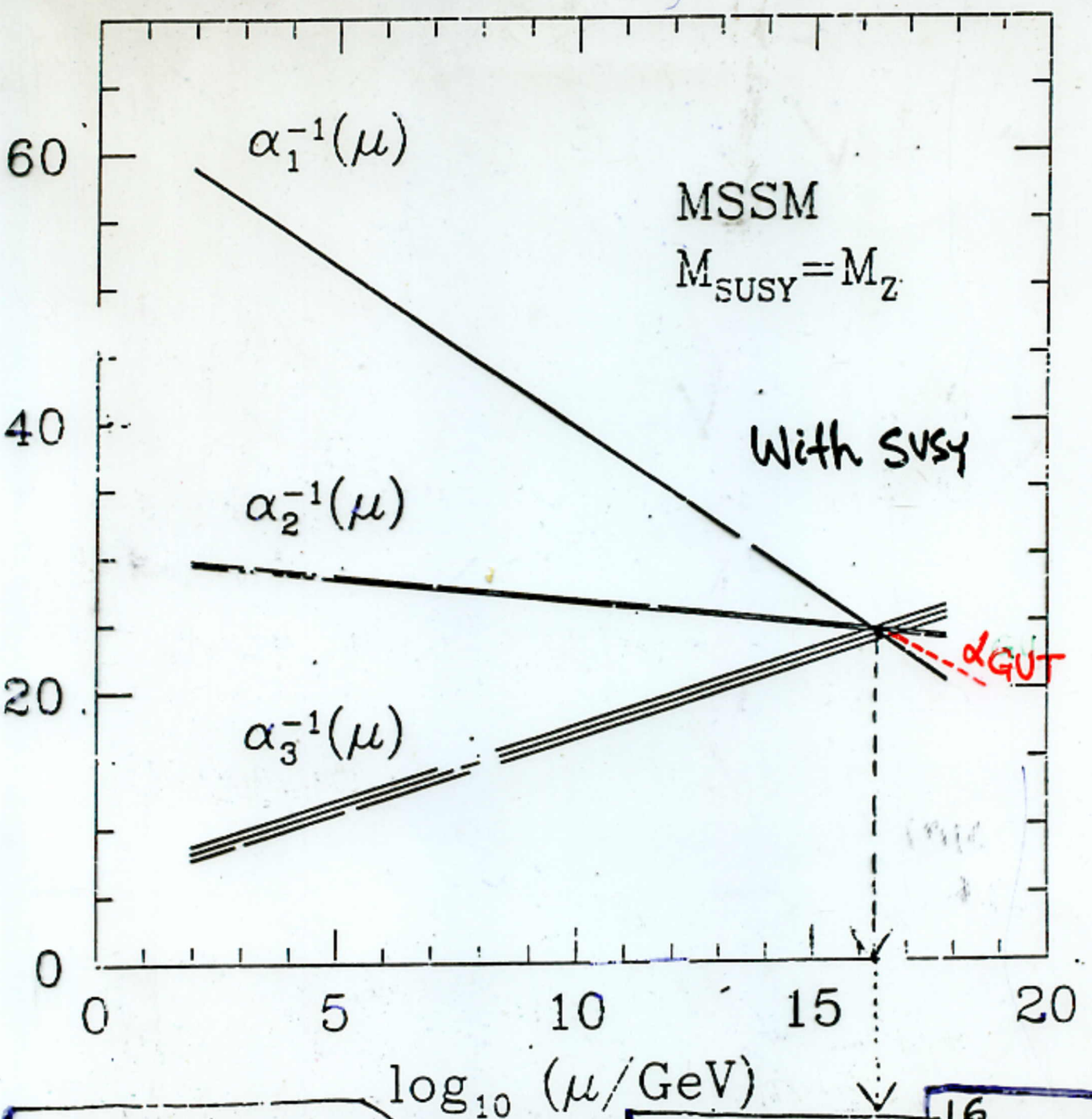
8) $\theta(\nu_\mu - \nu_\tau) \approx \pi/4 \leftrightarrow V_{cb} = 0.04$

9) LEPTOGENESIS $\rightarrow Y_B \sim 10^{-10} \rightarrow \nu_R$/B-L

SUCCESS of All 9 Features Non-Trivial!

TOGETHER MAKE A STRONG CASE FOR SUSY GRAND UNIF // SIMULT. FOR AN EFF. SYMMETRY LIKE SO(10) OR MINIMALLY A STRING-DERIVED G(224) SYMMETRY

Gauge Coupling Unification With SUSY



Supports SUSY Unification

$M_{GUT} \approx 2 \times 10^{16}$ GeV

$\sin^2\theta_W(m_Z)_{th} = 0.2315 \pm .003$

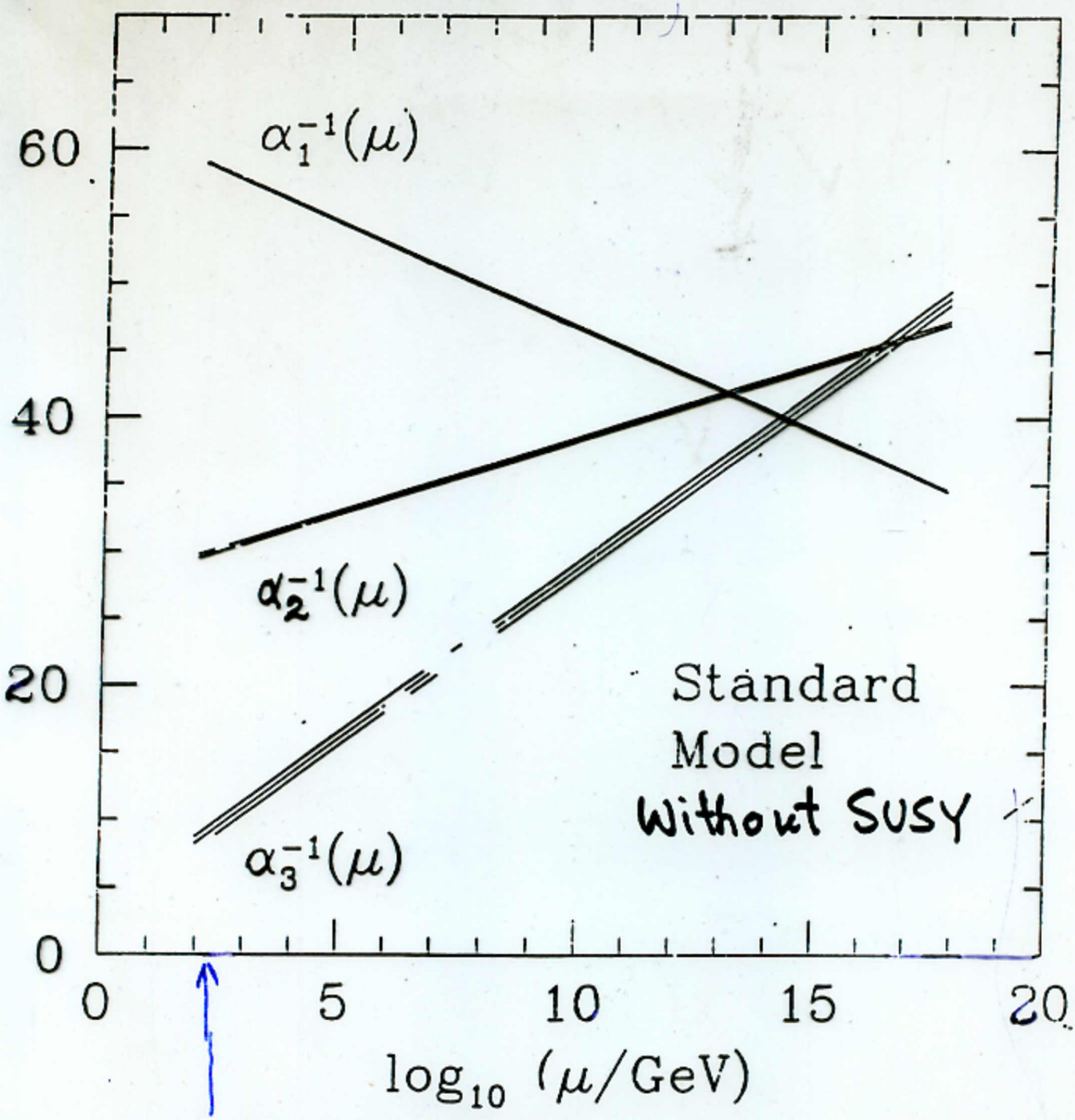
$\sin^2\theta_W(m_Z)_{EXPT} = 0.23124 \pm .00017$

$\alpha_3(m_Z)^{-1}_{theory} \simeq 0.125 - 0.13$

$\alpha_3(m_Z)_{obs} = 0.118 \pm .003$

GUT THRESHOLD CORRECTION

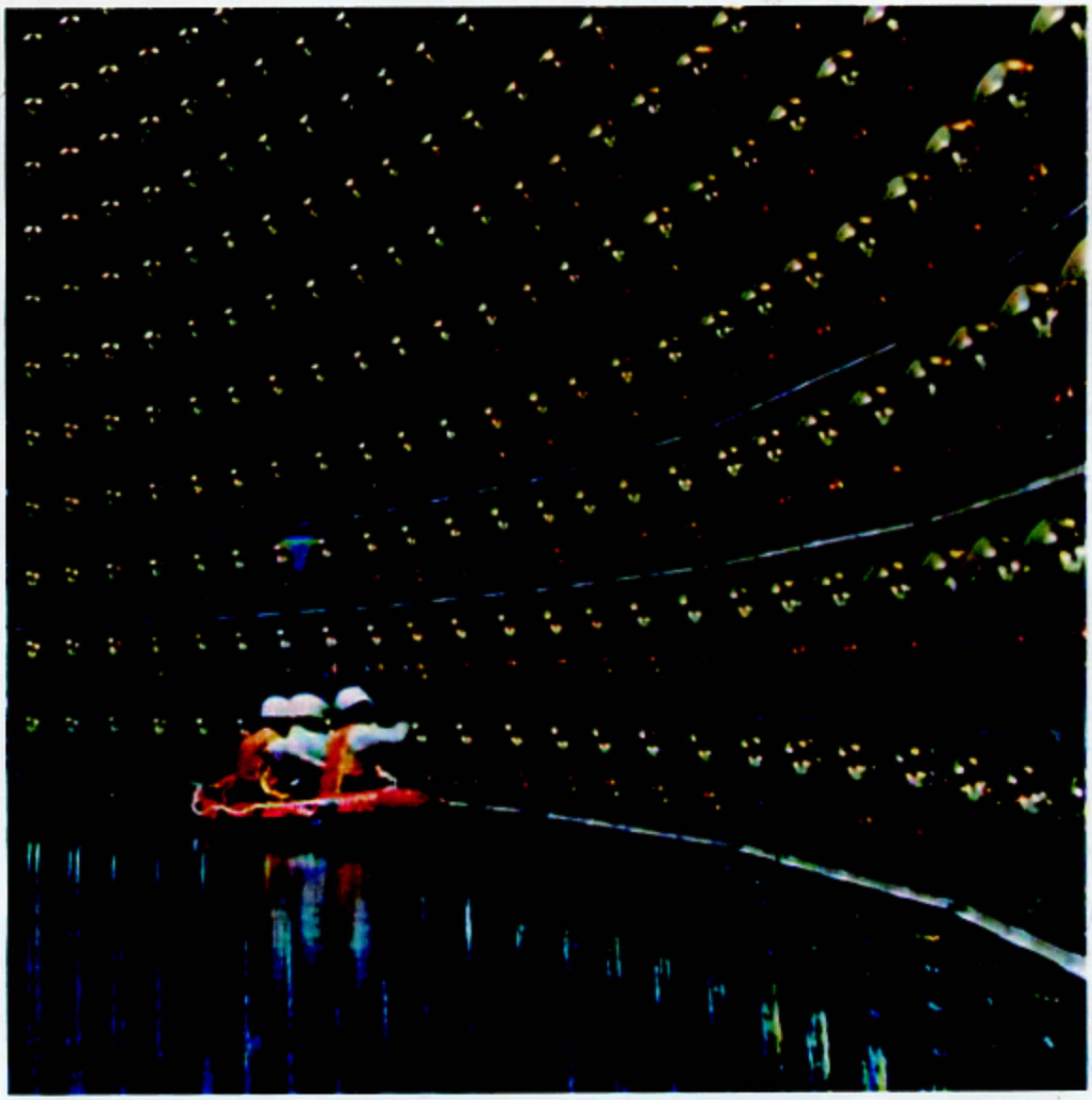
Coupling Unification Without SUSY



α_i's Measured at LEP

at $\sim$ 100 GeV

a



SUPERKAMIOKANDE water Cerenkov detector
Discovery of Atmospheric Neutrino Oscillation, 1998

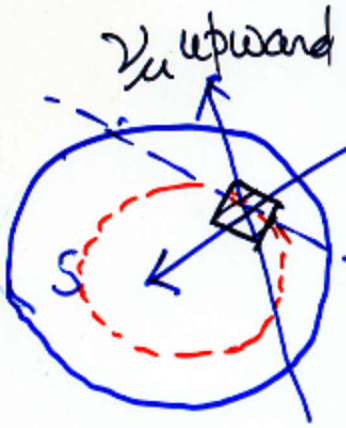
Discovery of ν Oscillations

(1) Atmospheric (SuperK) 1998

50 KT Water Cherenkov Detector

$\pi^+ \to \mu^+ \nu_\mu \to \bar{\nu}_\mu e^+ \nu_e$

For $E_\nu >$ A Few GeV cosmic ray flux isotropic



With MultiGeV ν's

$$\frac{\text{Flux up}(-1 < \cos\Theta_z < -0.2)}{\text{Flux Down}(+.2 < \cos\Theta_z < +1)} = 0.54 \pm 0.04$$

$\Rightarrow \nu_\mu$ has converted to $\nu_x = \nu_\tau$

$\Downarrow$

$$|\Delta m^2_{23}(\nu)| = |m_3^2 - m_2^2| = (2.5 \pm .3) \times 10^{-3}\ eV^2 \approx (1/20\ eV)^2$$

$$\sin^2 2\Theta_{23} = 1.02 \pm .04$$

$$P(\nu_\mu \to \nu_x)_L = \sin^2 2\Theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$= \sin^2 2\Theta \sin^2\left[\frac{1.27\ \Delta m^2(eV^2)\ L(Km)}{E\ (GeV)}\right]$$

ν Mass with ν_L & ν_R are in SU(4) - Color

(1) Can have DIRAC Mass

$$h^i_\phi \; \bar{\nu}^i_R \nu^i_L \langle \phi \rangle + h.c \qquad (\Delta L = 0)$$

$$\Rightarrow m(\nu^i)_{Dirac} = h^i_\phi \langle \phi \rangle \approx h^i_\phi \, (200\ GeV)$$

---

(2) BUT ν_R Can have Superheavy Majorana Mass

$$h_M \nu_R^T \nu_R \langle \Sigma^{eff} \rangle \Rightarrow \boxed{M(\nu_R) = h_M \langle \Sigma \rangle \sim h_M\,(GUT\text{-}Scale)}$$

$\Delta L = -2$

$$\begin{array}{c} \\ \nu_L \\ \bar{\nu}_R \end{array} \begin{bmatrix} \nu_L & \bar{\nu}_R \\ 0 & m(\nu)_D \\ m(\nu)_D & M(\nu_R) \end{bmatrix} \rightarrow \approx \begin{bmatrix} \nu_L & \bar{\nu}_R \\ -m(\nu_D)^2/M(\nu_R) & 0 \\ 0 & M(\nu_R) \end{bmatrix}$$

$$\Rightarrow \text{SeeSaw} \qquad m(\nu_L) \simeq m(\nu)_D^2 / M(\nu_R)$$

$$\Big\downarrow \qquad \ll m(\nu_D)$$

NATURALLY SUPERLIGHT

III A) Insight From SuperK Result: $\sqrt{\Delta m^2_{23}} \approx 1/20$ eV

49

SeeSaw
ignore mixing for a moment

$$m(\nu_L^\tau) \approx \frac{m(\nu_{Dirac}^\tau)^2}{M(\nu_R^\tau)}$$

(a) $m(\nu_{Dirac}^\tau) \approx m_t(M_X) \approx 120\,GeV$ ⇐ SU(4) - Color, ~~SU(5)~~, ~~[SU(3)]^3~~

$m_b^\circ \approx m_\tau^\circ$

(b) Get $M(\nu_R^\tau)$ from SUSY Unif. Scale: $M_X \approx 2\times10^{16}$ GeV

$$\frac{f_{33}\,16_3\,16_3\langle\overline{16}_H\rangle\langle\overline{16}_H\rangle}{M} \Rightarrow M(\nu_R^\tau) \sim \frac{(2\times10^{16}\,GeV)^2}{10^{18}\,GeV}$$

$f_{33} \approx 1$; $M \to \sim 10^{18}$ GeV

$$\approx 4\times10^{14}\,GeV\ (1/2 - 2)$$

$$m(\nu_L^\tau) \sim \frac{(120\,GeV)^2}{4\times10^{14}\,GeV} \approx \left(\frac{1}{30}\,eV\right)\left(\frac{1}{2}\text{ to }2\right)$$

Also get $m(\nu_L^\mu) \sim \frac{m(\nu_L^\tau)}{10} \Rightarrow \sqrt{\Delta m^2(\nu_2\nu_3)_{Th}} \approx \left(\frac{1}{30}\,eV\right)\left(\frac{1}{2} - 2\right)$

Thus SuperK result brings to light the existence of ν_R // reinforces the ideas of
a) SeeSaw // b) SU(4) Color // & c) SUSY Unif

Summary on Fermion Masses & Mixings (Babu, Pati Wilczek)

Predictions	Observations
$m_b(m_b) \approx (4.7-4.9)$ GeV	≈ 4.2 GeV
$\sqrt{\Delta m^2_{23}(\nu)} \sim (1/24\ \text{eV})(\frac{1}{2}-2)$	$\approx (1/15 - 1/25)$ eV (*)
$V_{cb} \approx 0.043$	≈ 0.04
$\sin^2 2\theta^{osc}_{\nu_\mu \nu_\tau} \approx$ [0.92] $\leftrightarrow$ [0.995]	$\approx 0.92 \leftrightarrow 1$
$M_{\nu_3}/m_{\nu_3} \approx 1/10 - 1/5$	
$V_{us} \approx 0.23$	≈ 0.22
$\lvert V_{ub} \rvert \approx 0.0032$	$\approx 0.003 - 0.004$
$m_d(1\text{GeV}) \approx 8$ MeV	$\approx 6-8$ MeV

$m(\nu_2) \approx (2-10)\times 10^{-3}$ eV $\leftrightarrow$ { SMA $\sim 3\times 10^{-3}$ eV ; [LMA $\approx 7\times 10^{-3}$ eV] }

$m(\nu_1) \sim$ (1 to few) $\times 10^{-3}$ eV

Consistent with the framework

$M(\nu_R^3, \nu_R^2, [\nu_R^1]) \approx (10^{15}, 2\times 10^{12}, (\frac{1}{3}-3)\times 10^{10})$ GeV

Just right for Lepto/Baryogenesis

NOTE: Masses Necessarily Hierarchical.

ν Masses $\leftrightarrow$ Matter - Anti Matter Asymmetry

Starting at baryon-symmetric Universe at $t=0$ (BigBang) or just at the beginning of reheating after inflation, what eventually caused

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11} \quad \text{(WMAP)}$$

Sakharov Need (1967):
1. C & CP Non-Conservation
2. $\Delta B \neq 0$ Processes
3. Thermodynamic Non-equilibrium

Most Promising Explanation

$$M(\nu_R)\ \nu_R^T \nu_R + h.c \quad (\Delta L = \pm 2)$$

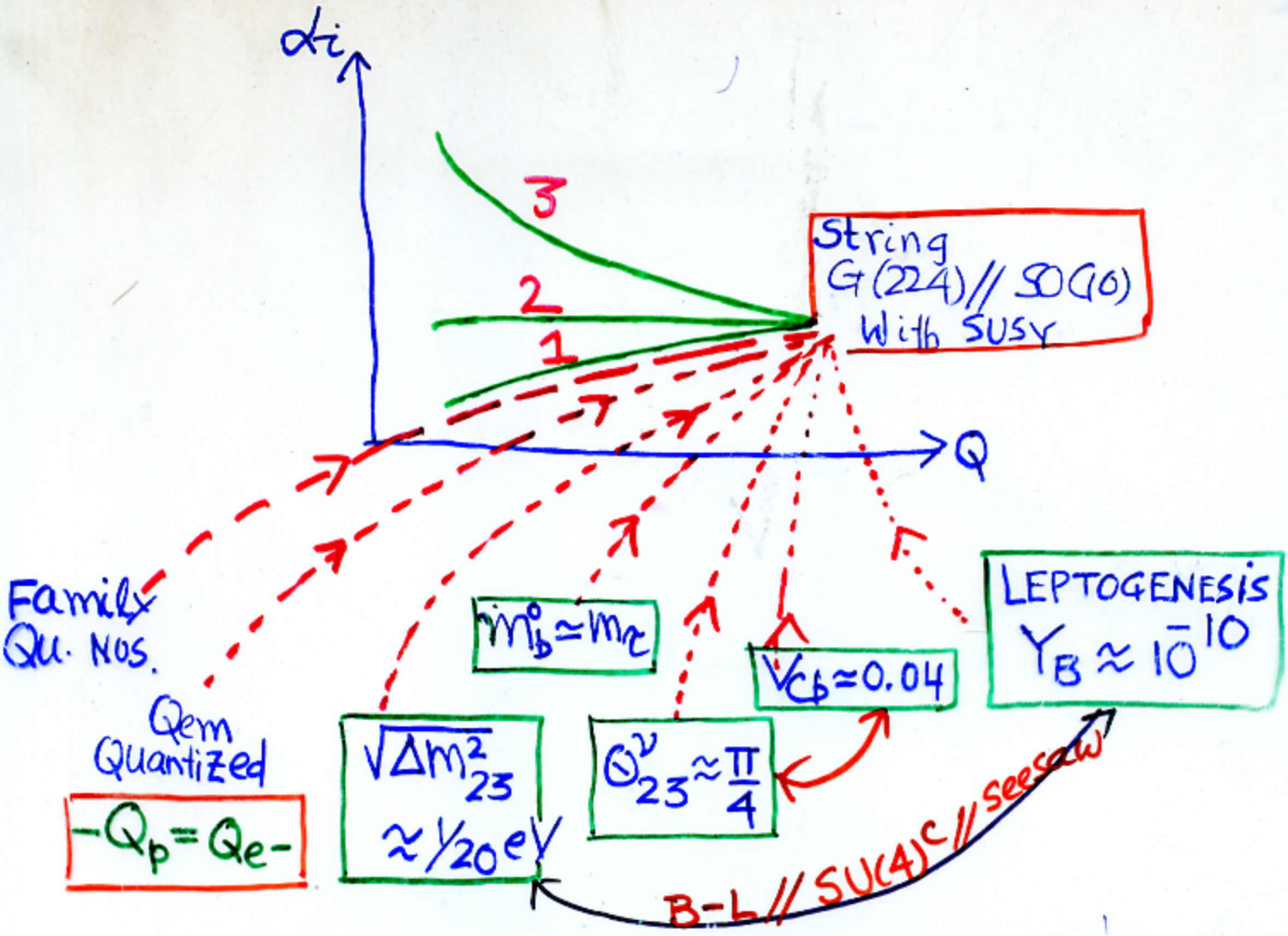
Fukugita Yanagida $\Rightarrow$ $n_\ell \neq n_{\bar{\ell}}$ With $T_{RH} \sim 10^6 - 10^8$ GeV

$Y_L \neq 0 \xrightarrow{SU(2)\times U(1)} Y_B \neq 0$ (sphaleron Effect)

Quantitatively NATURALLY Get

$$Y_B \approx (10-100) \times 10^{-11} \quad \text{(As Needed)}!$$

For $\Phi_{CP} \sim 1/10 - 1$



ALL THESE FEATURES & MORE HANG TOGETHER NEATLY IN A SINGLE UNIFIED FRAMEWORK → HARD TO IMAGINE THIS CAN BE MERE COINCIDENCE

⇓

TWO MISSING PIECES

- PROTON DECAY → Need NEXT GEN. DETECTOR
- SUPERSYMMETRY → LHC

S-14 Superstring / M-Theory

Green, Schwarz (84) / Witten (95) .....

$d = 10 / 11$

- Point Particle → Tiny String $\sim 10^{-32}$ cm + Vibrational Modes

$$\begin{cases} (q, \ell)_{1/2} + (\text{gluons}, W, Z, \gamma)_1 \\ + (\text{Higgs})_0 + (\text{graviton})_2 + \cdots + \text{SUSY Partners} \end{cases}$$

1 Dim World Line → 2D World Sheet

- THE MOST UNIFYING THEORY OF ALL
- Predicts gravity, together with the other Forces – Unifies all four forces
- Different Elementary Entities → Diff. Vibrational Modes of one & the Same Entity – Unifies All matter
- Good Quantum Theory of Gravity
- In principle Can go Sufficiently beyond Grand Unification in predictions
  (i) # Families = 3 ?
  (ii) Hierarchical Masses & Mixings ?

- In practise, not yet possible to extract either a unique or a non-densely discrete set of Solns for the ground state of the theory.

→ Thus not yet possible to compare String Theory with experiments

→ The Theory still poorly understood both in formulation and in its non-perturbative aspects

→ Very likely Some essential ingredients still missing

→ A GREAT CHALLENGE TO FIND A TRULY UNIFIED QUANTUM THEORY OF GRAVITY, which is PREDICTIVE

Einstein → Friedman / Lemaitre :

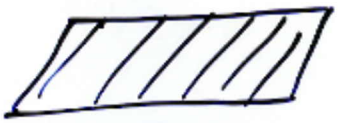
$d(t) = R(t)\, d(t_0)$ — Universal Scale Factor

$$\left(\dot{R}/R\right)^2 + \frac{K}{R^2} = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3}$$

If $\Lambda = 0$

K = curvature of space > 0 +Ve curvature Sphere (closed, finite)

$K < 0$  Saddle (Infinite, open)

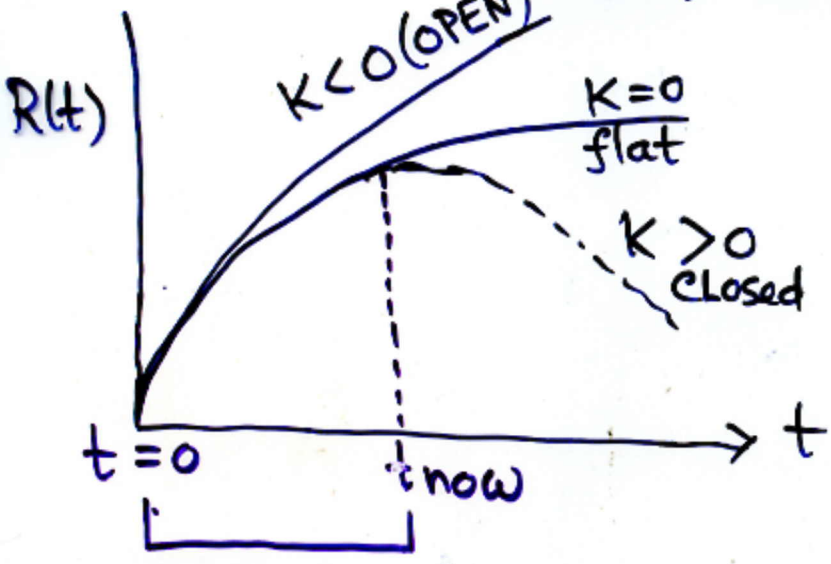
$K = 0$  Flat (Infinite, open)

$$H(t) \equiv \dot{R}/R \Rightarrow d(t) = v(t)/H(t)$$

Big Bang : Universe Now Expanding.

⇒ Going Backwards in time, separations among the objects in the Universe → 0

$d(t) = R(t)\, d(t_0)$



If v Const

$t_{now} = d_{now}/v = \frac{1}{H}$

≈ 15 billion yrs.

Allowing for varying $H(t)$

$t_{Age} \approx (13.7)$ billion yrs

WMAP

Critical density

$$\rho_c \equiv 3H^2/8\pi G \approx 8 \times 10^{-30}\ gm/cm^3$$

(For H = 17 Km/sec/ 1 million Lt/yr)

$$\rho_{visible} \approx 1/20\ \rho_{critical}$$

But see Strong evidences for dark matter

$$\rho_{Tot} = \rho_{vis} + \rho_{dark\ Matter} + \rho_{Dark\ Energy}$$

$$\Omega_{Tot} = \frac{\rho_{Tot}}{\rho_c} \approx 1$$

4% + 23% + 73%

1998 Supernova Ia / WMAP

Thermal History

From Einstein's Eqn: $t_{sec} \simeq \frac{1}{(KT)^2_{MeV}}$

Typical times Vs Temp

$t \to 0,\ KT \to \infty$

$T \simeq 10^{32}\ K \Rightarrow KT \sim 10^{19}\ GeV \Rightarrow t_{sec} \simeq 10^{-44}\ sec$ PLANCK TIME

$T \simeq 10^{29}\ K \Rightarrow KT \sim 10^{16}\ GeV \Rightarrow t \approx 10^{-38}\ sec$ GRAND UNIF ERA

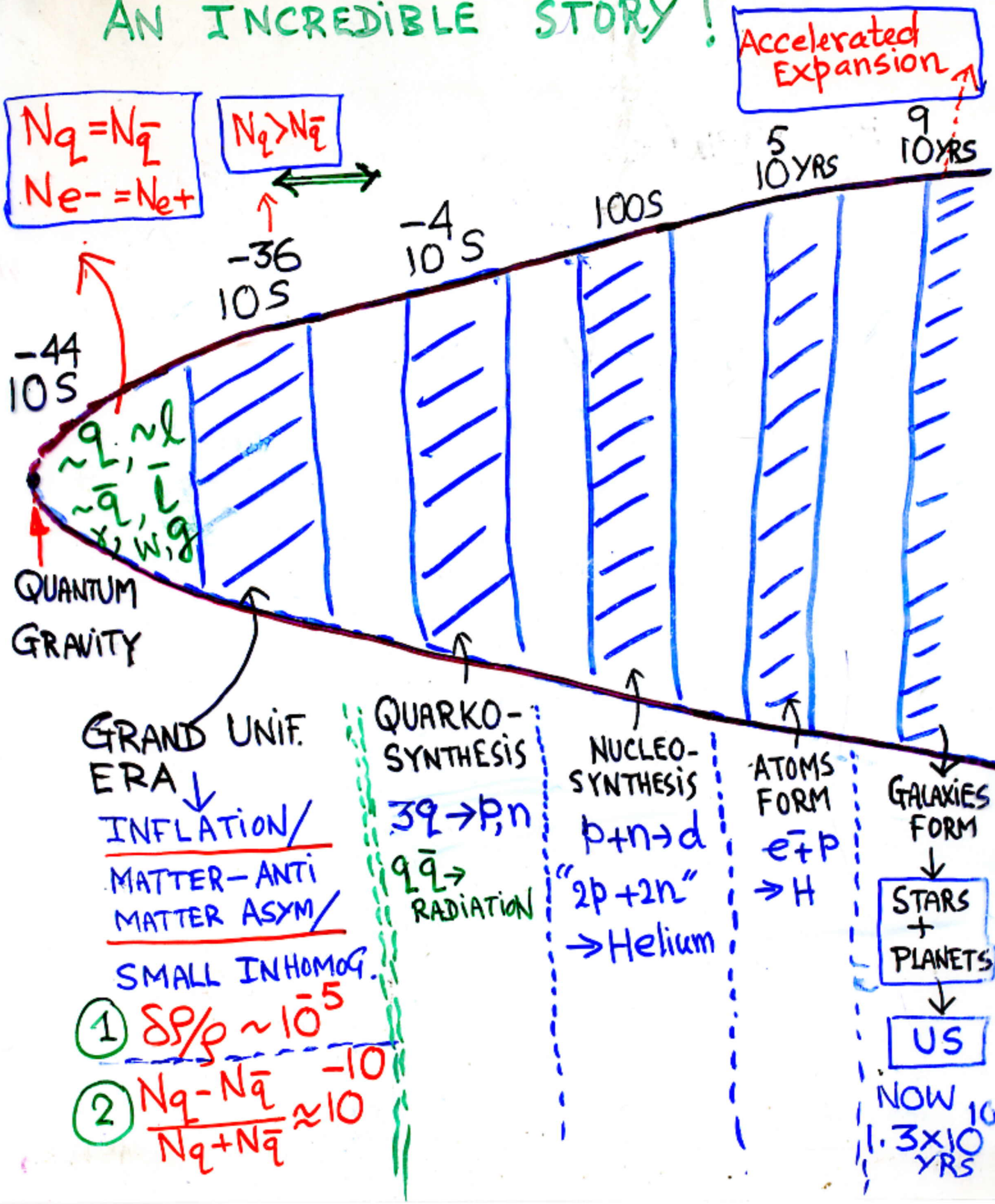
$KT \sim 300\ MeV \Rightarrow t \approx 10^{-5}\ Sec$

$KT \sim 1/10\ MeV \Rightarrow t \approx 100\ sec.$

$$1\ MeV = (K)(10^{10}\ Kelvin)$$

THE EXPANDING UNIVERSE: BIG BANG TO NOW

AN INCREDIBLE STORY !



ON THE EXPERIMENTAL FRONT

EXPECT GREAT INSIGHTS FROM

1) LARGE HADRON COLLIDER (LHC)

- GENEVA (2007)

pp or $\bar{p}p \rightarrow X$ ($E_{cm} \sim 14$ TeV, dist $\sim 10^{-18}$ cm)

2) Facilities in the SKY

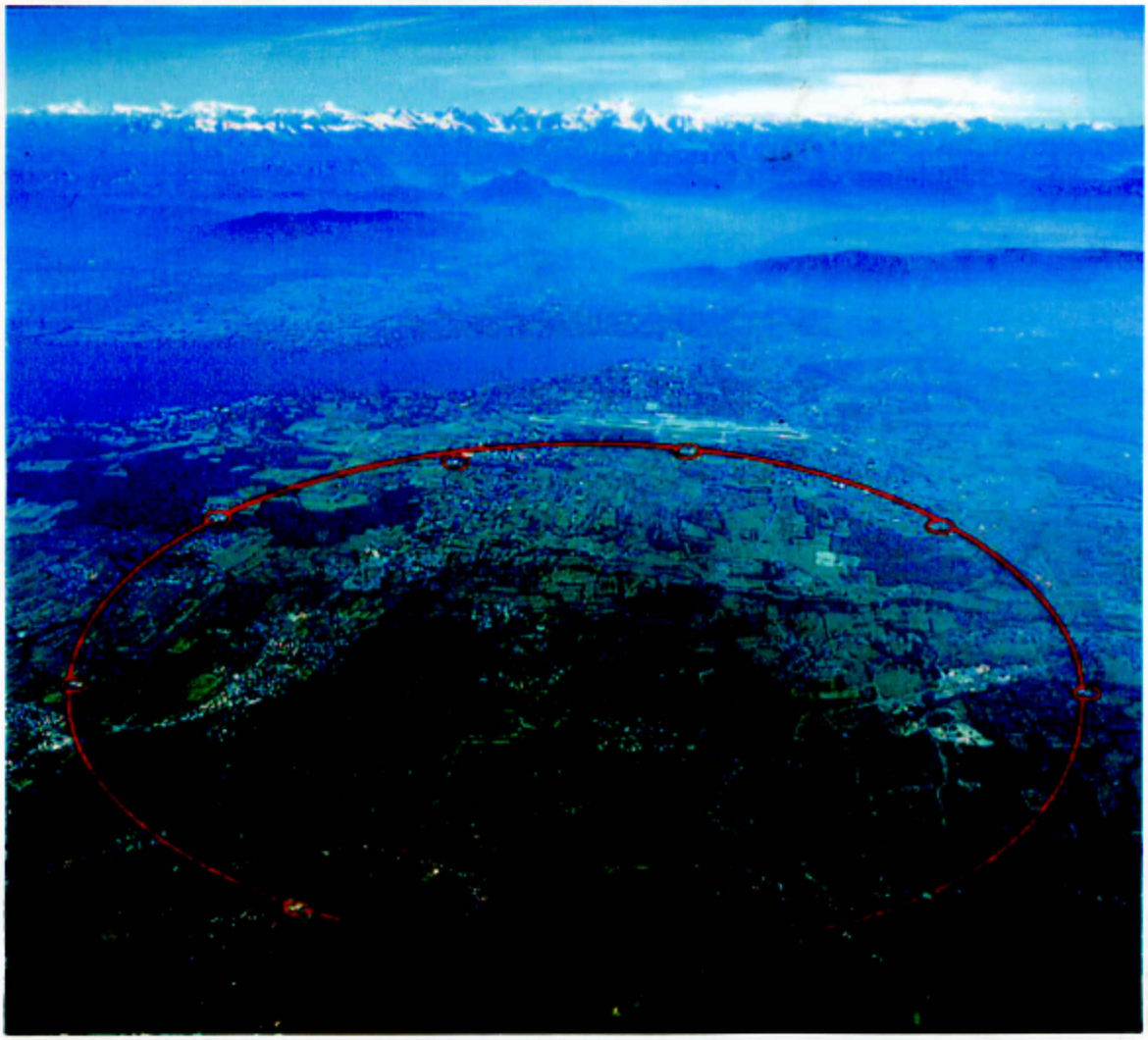
Hubble / COBE / WMAP / PLANCK / GROUND BASED TELESCOPE

PRECISION STUDIES OF COSMIC MICROWAVE BACKGROUND RADIATION (CMBR) // GALAXIES, STARS // → EARLY UNIVERSE

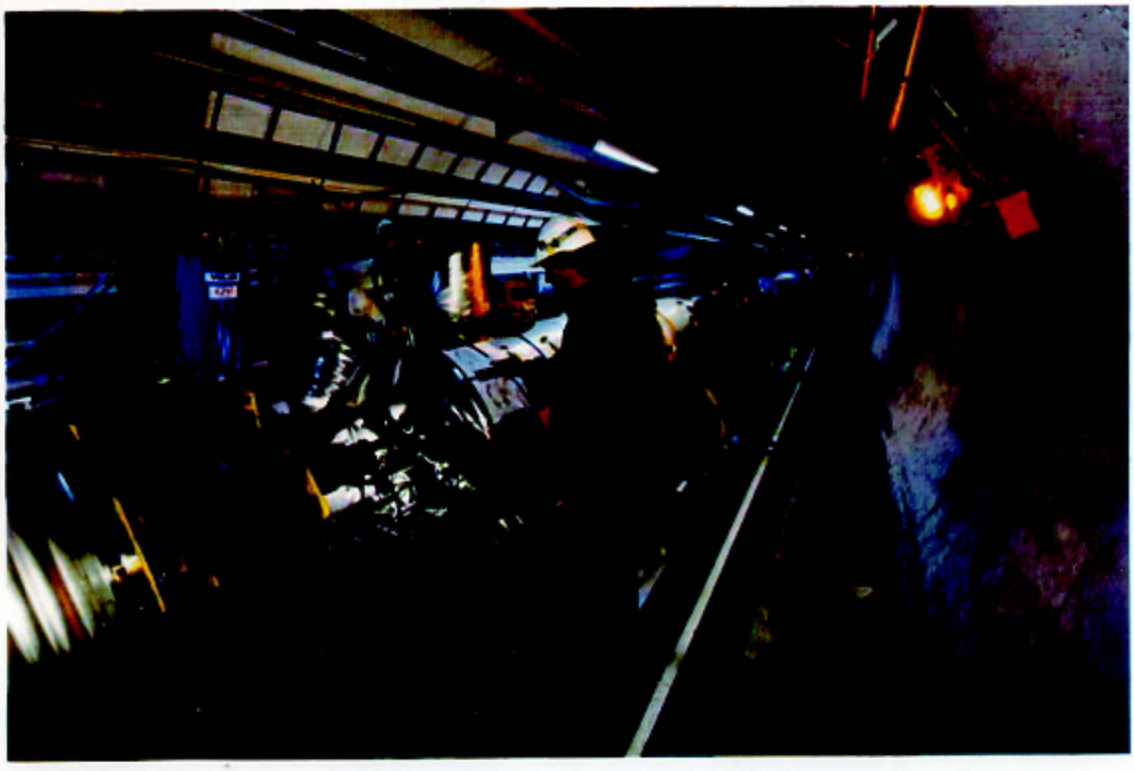
3) Major Underground Detector

- In Planning (MEGATON OF WATER)

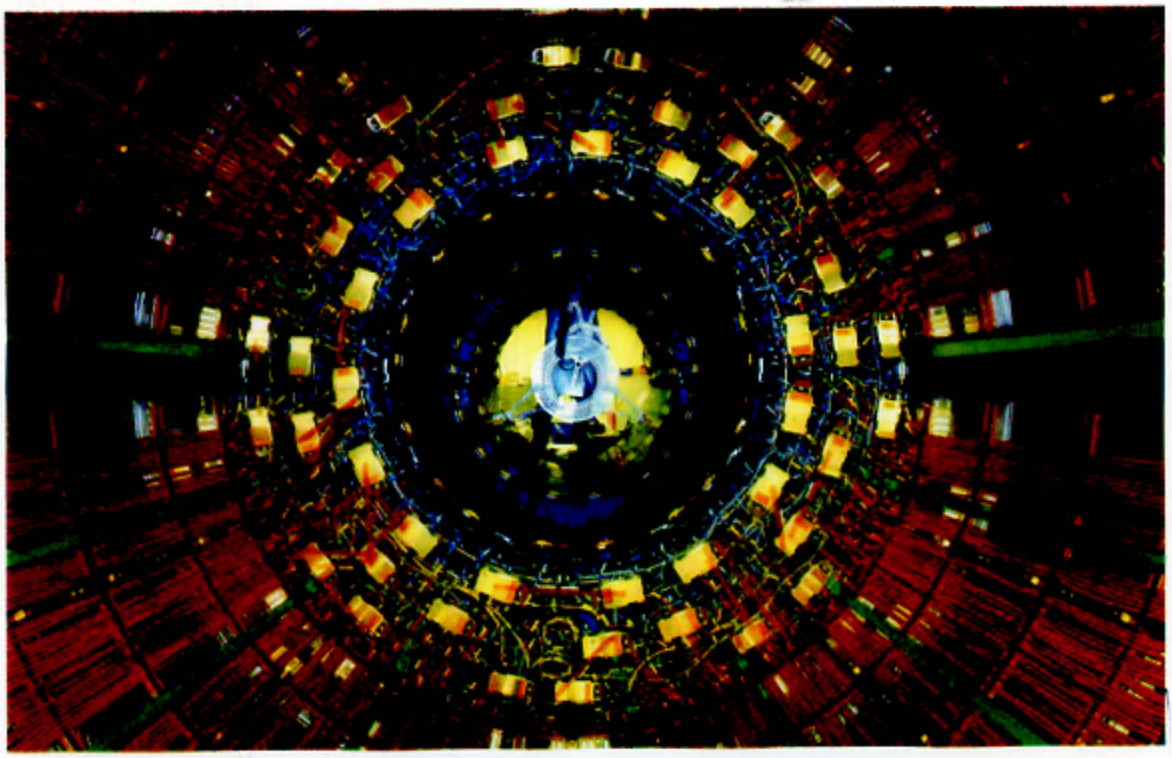
Study { Proton Decay ($p \rightarrow e^+ \pi^0$, $p \rightarrow \bar{\nu} K^+$)
NEUTRINO OSCILLATIONS
SUPERNOVA
& MORE



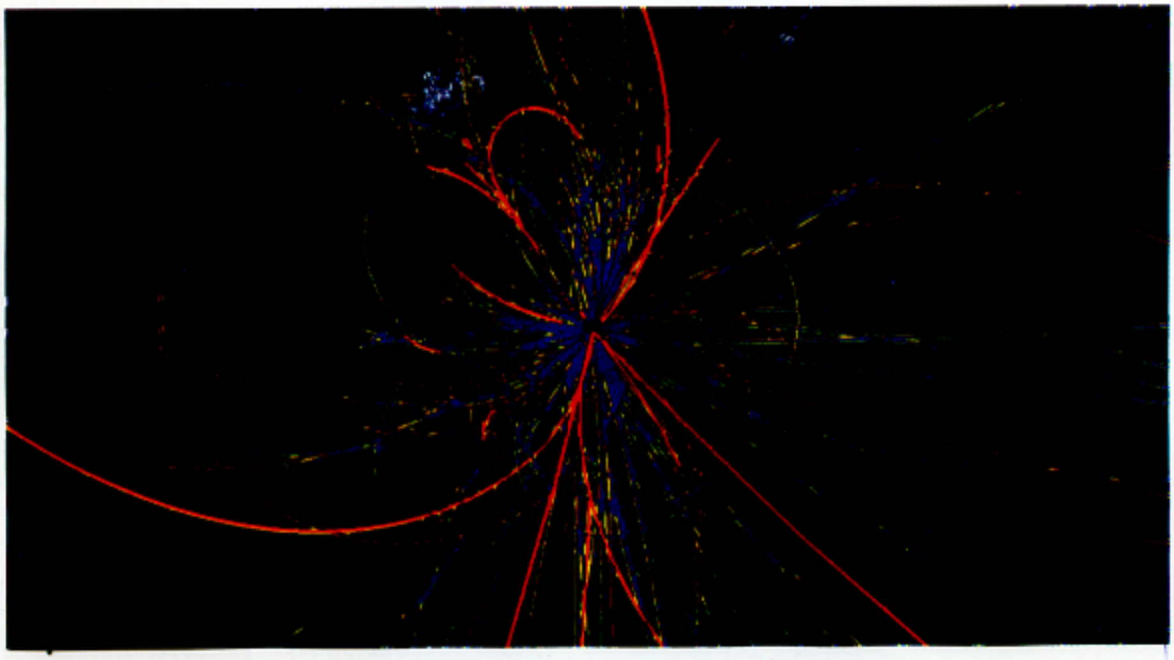
LHC RING OVER SWITZERLAND AND FRANCE (27 k.m. Ring)



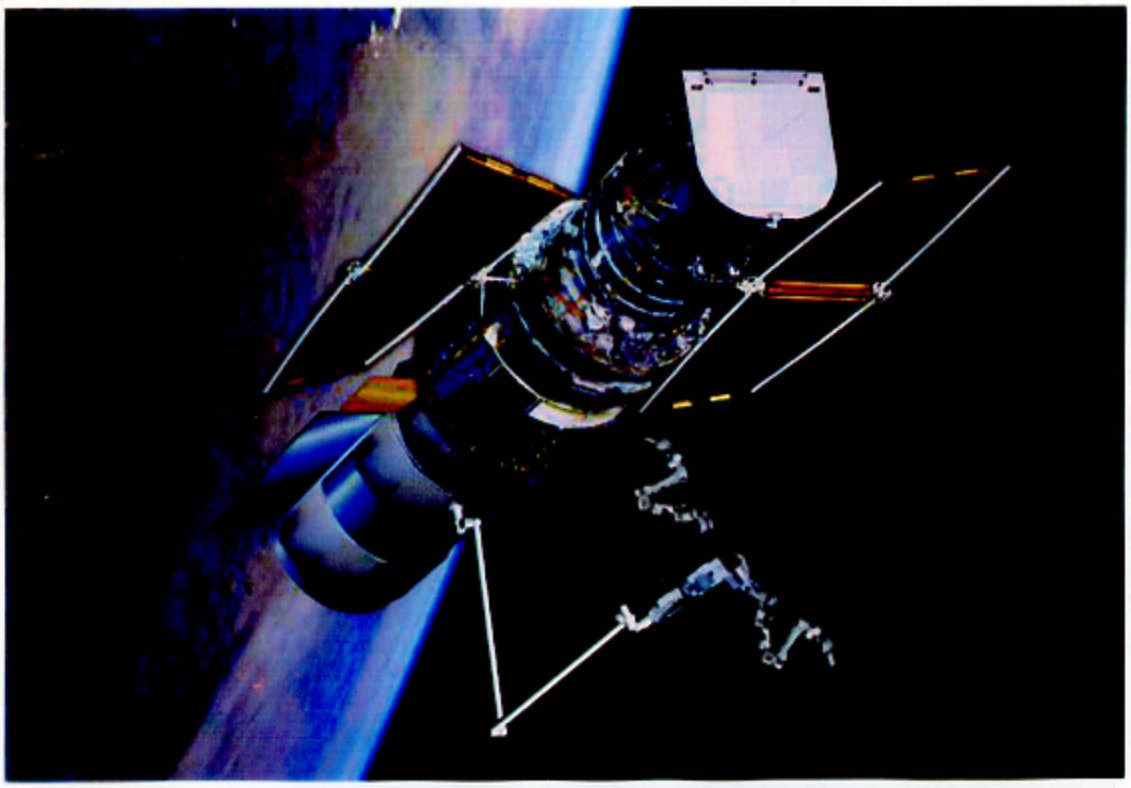
LHC - SECTION



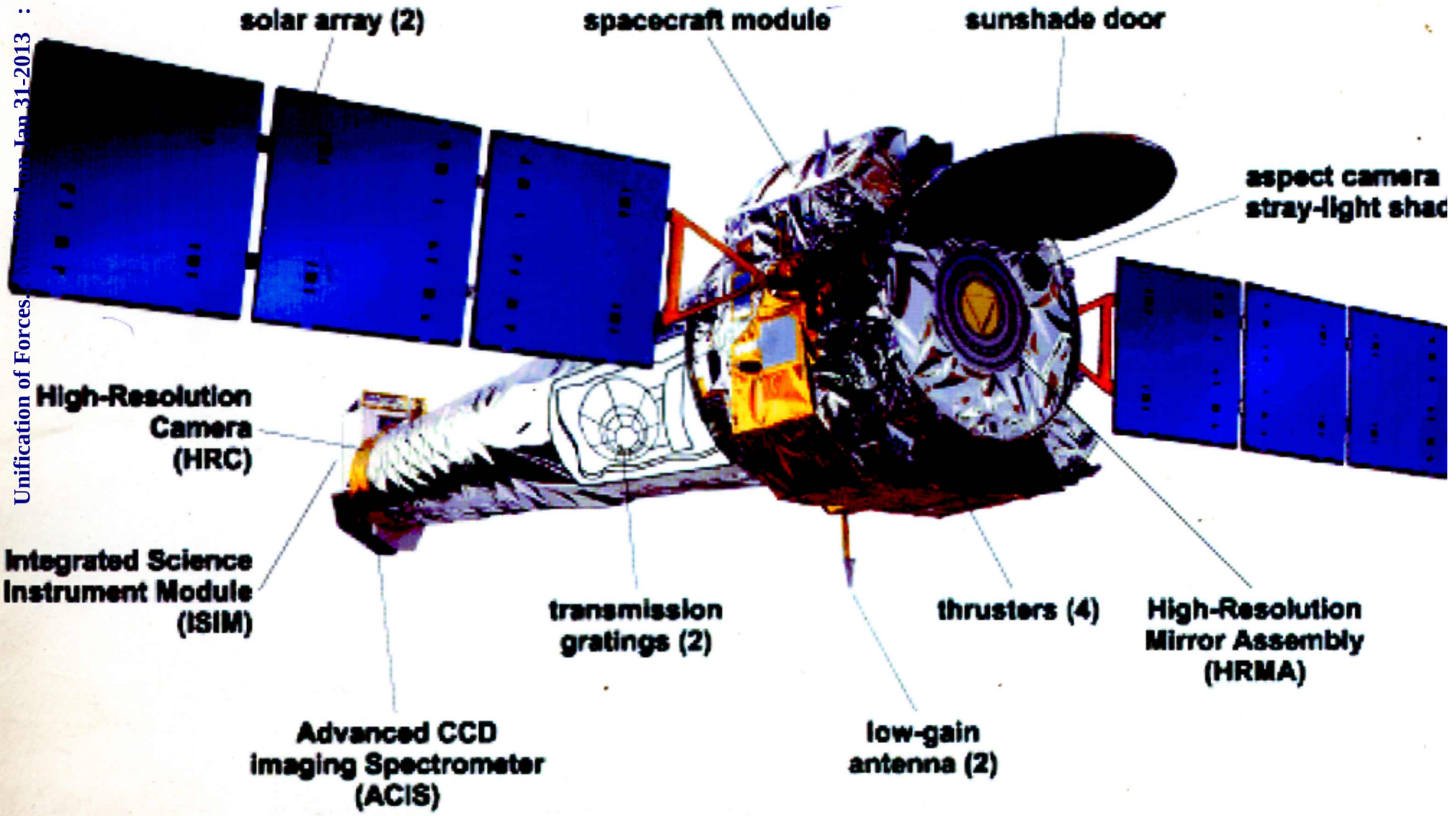
LHC - DETECTOR

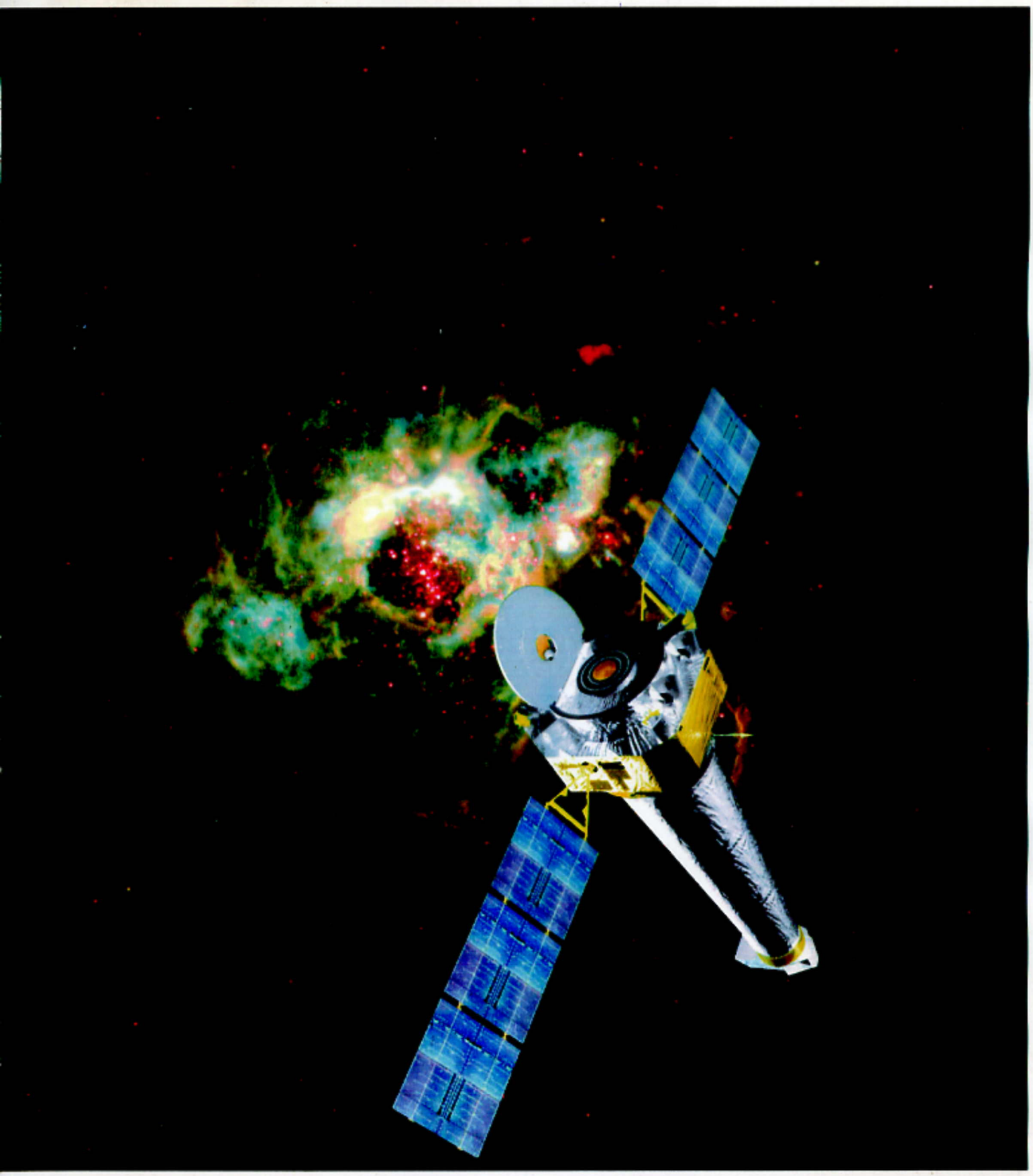


LHC Interactions

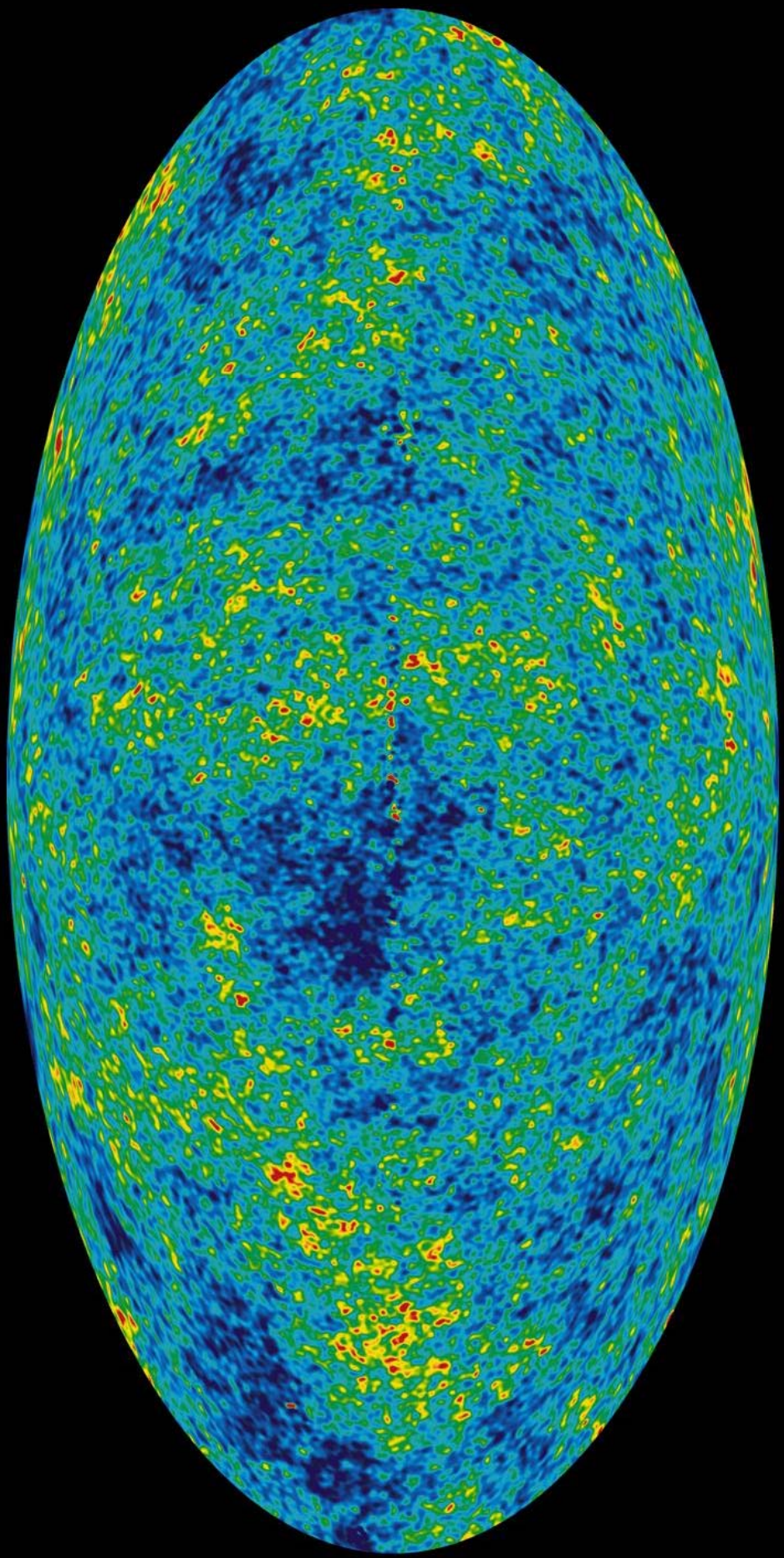


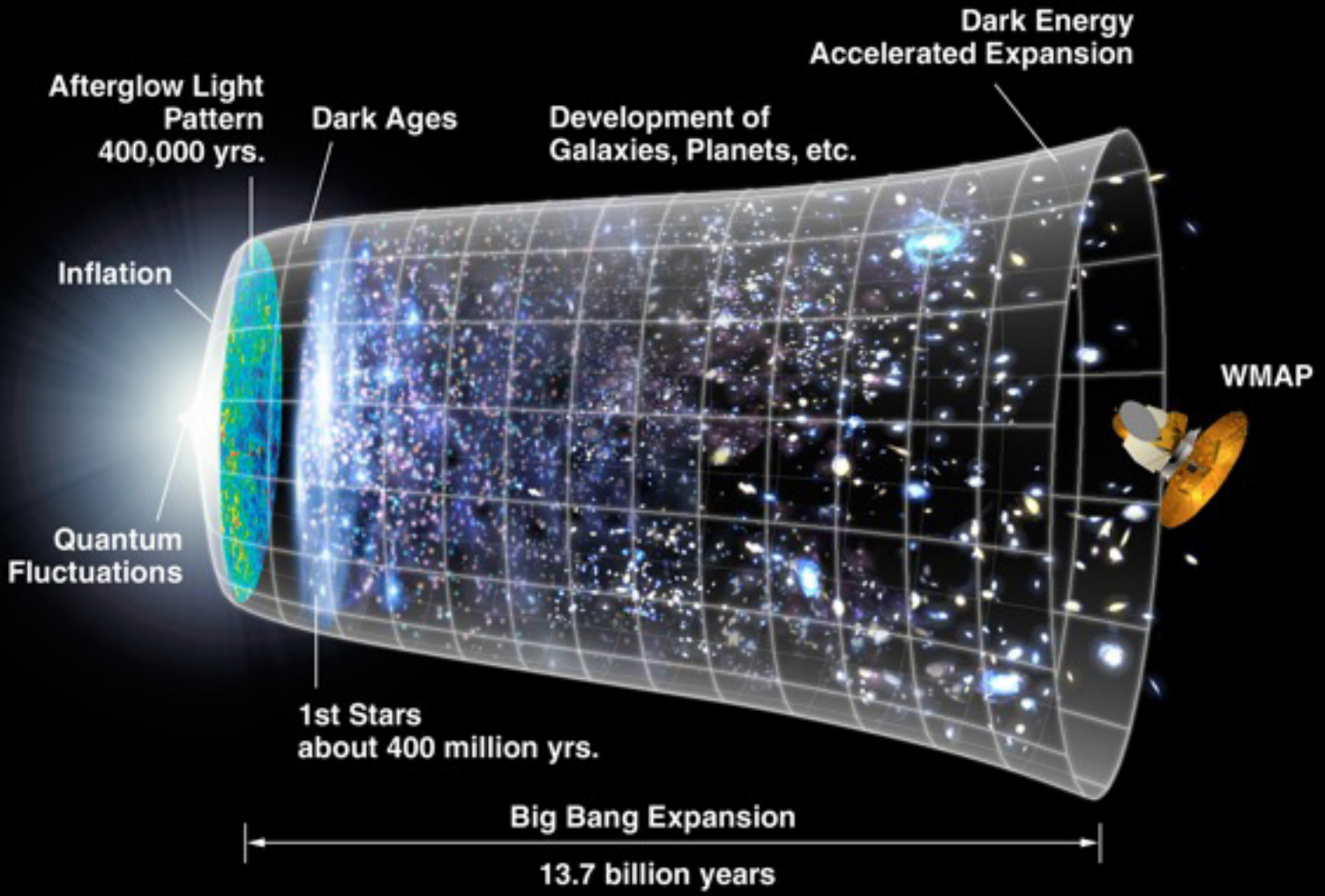
HUBBLE SPACE TELESCOPE






SCIENCEphotoLIBRARY



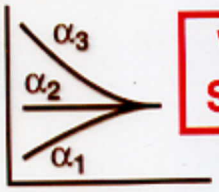

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

VERY SMALL

10^{-16}cm to 10^{-30}cm

EW UNIF ⊕ QCD → Grand Unification

Standard Model ~100 GeV

1. Spectrum of (q, ℓ)
2. Quantize Q_{em}
3. 

With SUSY
4. "m(ν_3)" ~1/20 eV
5. $(n_{b/s})_{Theor}$ ~ 10^{-10}-10^{-11}
6. SUSY LSP or Axion as CDM

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \approx$$

10^{-32}cm — String/M Theory

dim. d = 10/11

Scope for a Truly Unified Theory with Good Quantum Gravity

Still Evolving

VERY LARGE

10^{28}cm

Stand. Big Bang Model ⊕ Inflation

T ~ 10^{16} - 10^{14} GeV; t ~ 10^{-38}-10^{-34} sec

T_{rh} ~ 10^{9}-10^{6} GeV

1. Gross Homog/Isotropy
2. Flatness: $\Omega_{Tot}^{obs} = \Omega_M + \Omega_\Lambda$ = 1.01 ± 0.01
3. $\delta\rho/\rho \sim \delta T/T \sim 10^{-5}$
4. $(n_{b/s})^{obs} \approx 10^{-10}$
5. Dark Matter: $\Omega_{CDM} \approx 0.23$; $\Omega_B \approx 0.04$
6. • Galaxy Formation
   • Stars Born / Shine / Die
7. Evolution of Life!
8. Dark Energy $\Omega_\Lambda^{obs} = 0.73$

A Total Mystery

7-2006
8733A2

CONCLUSION

EINSTEIN'S DREAM OF UNIFYING GRAVITY WITH EM FORCE, & from THE PRESENT VIEWPOINT UNIFYING GRAVITY WITH EM, WEAK & STRONG FORCES STILL REMAINS TO BE FULFILLED → THOUGH GREAT PROGRESS HAS OCCURRED IN (LAST 4 DECADES)

→ STRONG EVIDENCE FOR GRAND UNIFICATION (WEAK, EM & STRONG FORCES) → CRUCIAL FURTHER TEST (PROTON DECAY) NEED MEGATON DETECTOR

→ STRING/M THEORY SHOWS PROMISE TO UNIFY All THE FORCES // REMAINS A CHALLENGE

→ WHATEVER THE EVENTUAL FORM OF THE "ULTIMATE" THEORY, ONE EXPECTS TO SEE UNITY BEHIND FAR GREATER DIVERSITY

→ A SYNTHESIS FAR GREATER THAN ONE CAN CONCEIVE OF AT PRESENT

→ THAT is THE CHALLENGE !