

ESA Cosmic Visions
Workshop
15-16 Sept 2004, UNESCO

BEYOND GENERAL RELATIVITY

[TOWARD QUANTUM GRAVITY]

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IHES

GENERAL RELATIVITY

CV1

- 4-DIMENSIONAL MANIFOLD : x^μ ; $\mu=0,1,2,3$
- GRAVITATION = GEOMETRY : $ds^2 = g_{\mu\nu}(x^\lambda) dx^\mu dx^\nu$
- $S_{\text{TOT}} = \frac{c^4}{16\pi G} \int \frac{d^4x}{c} \sqrt{g} [R(g) - 2\Lambda] + \underbrace{\text{COSMOLOGICAL CONSTANT}}_{\text{COSMOLOGICAL CONSTANT}} + S_{\text{MATTER}}[\phi, A, H; \underbrace{g_{\mu\nu}; \alpha_a, m_a, \dots}_{\text{EQUIVALENCE PRINCIPLE}}]$

EQUIVALENCE PRINCIPLE

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

EXPERIMENTAL CONFIRMATIONS

• EQUIVALENCE PRINCIPLE TESTS

$$\left\{ \begin{array}{l} \left(\frac{\Delta a}{a} \right)_{\text{Be Cu}} = (-1.9 \pm 2.5) \times 10^{-12} \\ \left| \frac{\alpha_{\text{Dklo}} - \alpha_{\text{Now}}}{\alpha} \right| \lesssim 10^{-7} \end{array} \right.$$

• SOLAR SYSTEM TESTS

CASSINI

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

LUNAR LASER RANGING

$$4(\beta - 1) - (\gamma - 1) = -0.0007 \pm 0.0010$$

BINARY PULSAR TESTS

PSR 1913+16
PSR 1534+12
PSR 1141-6545
PSR 0737-3039

3 (4) INDEPENDENT CONFIRMATIONS
OF REALITY OF GRAV. RADIATION

$\sim 10^{-3}$

2+1+3 = 6 CONFIRMATIONS
OF G.R. STRONG-FIELD REGIME

$\sim 10^{-2}$

BEYOND GENERAL RELATIVITY

CV2

- WHY A CLASSICAL MANIFOLD x^μ ? $[x^\mu, x^\nu] \neq 0$?
- WHY A DYNAMICAL GEOMETRY? $\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$?
- WHY A LOCALLY MINKOWSKIAN GEOMETRY: $dx \rightarrow 0$: $\eta_{\mu\nu}$?
- WHY $D = 4$? KALUZA-KLEIN ~ 1920 $D=5 \Rightarrow \begin{cases} g_{55}, g_{5\mu} \\ g_{\mu\nu} \end{cases}$
- WHY EQUIVALENCE PRINCIPLE, i.e. WHY ONLY $g_{\mu\nu}(x)$ AS GRAVIT. FIELD?
- WHY $\Lambda_{\text{EFF}} \simeq 0$? $\rho_{\text{VAC}} = \frac{c^4 \Lambda}{8\pi G} \sim 10^{-120} M_P^4 \sim 10^{-60} M_W^4 \sim (10^{-3} \text{eV})^4$

EFFECTS OF $\hbar \neq 0$

PLANCK 1900 $\hbar \rightarrow l_P \equiv \sqrt{\frac{\hbar G}{c^3}} \simeq 1.6 \times 10^{-33} \text{ cm}$

$$\langle 4 | T_{\mu\nu}^{\text{MATTER}} | 4 \rangle = -g_{\mu\nu} \left\{ \sum_a \pm \int_0^{\omega_c} \frac{\hbar}{2} \sqrt{m_a^2 + k^2} \frac{d^3 k}{(2\pi)^3} \right\} + T_{\mu\nu}^{\text{EXCITATIONS}}$$

$$\rho_{\text{VAC}} \sim c_4 \omega_c^4 + c_2 m^2 \omega_c^2 + c_0 m^4 + c_{-2} \frac{m^6}{M_P^2} + \dots$$

HEISENBERG 1930: $G = \frac{\hbar}{M_P^2} = \frac{1}{\hbar \omega_P^2}$

$$\Rightarrow \frac{A_{\text{ONE-LOOP}}}{A_{\text{TREE}}} \sim \hbar G \int \frac{d^4 k}{k^2} \sim \hbar G \omega_c^2 \sim \frac{\omega_c^2}{\omega_P^2}$$

- WHY $\exists$ DIFFERENT TYPES OF INTERACTIONS?

- ELECTROMAGNETIC
- WEAK INT.
- STRONG INT.

GAUGE THEORIES

$$A_\mu^a$$

- GRAVITY

$$g_{\mu\nu}$$

- WHY $\exists$ SEVERAL HIERARCHIES

- COSMOLOGICAL $L_0 = ct_0 \sim 10^{28} \text{ cm} \gg \text{ANY } L_{\text{PARTICLE}}$
- PARTICLE $M_{\text{EW}} \sim 250 \text{ GeV} \ll M_{\text{Gauge UNIF}} \sim 10^{16} \text{ GeV}$ OR $M_P \sim 10^{19} \text{ GeV}$
- COSMOL. CONSTANT $\rho_{\text{VAC}}^{\text{THY}} \sim \omega_c^4 + m^2 \omega_c^2 + m^4 + \dots \gg \rho_{\text{VAC}}^{\text{OBS}} \sim (10^{-3} \text{eV})^4$

STRING THEORY

- ONLY CONCRETE PHYSICAL FRAMEWORK TO DISCUSS QUANTUM U.G.R.

- STARTING POINT:

$$\left\{ \begin{array}{l} \bullet \rightarrow \text{OR} \\ X^\mu(\tau) \quad X^\mu(\tau, \sigma) \end{array} \right.$$

QUANTUM MECHANICS: $\hbar$

SPECIAL RELATIVITY: $c, \eta_{\mu\nu}$

$$\frac{S_{\text{STRING}}}{\hbar} = -\frac{1}{2\pi \ell_s^2} \iint d^2A + \dots$$

TIME
SPACE

d^2A

$\sqrt{(\dot{X}^\mu X'^\mu)^2 - (\dot{X}^\mu)^2 (X'^\mu)^2}$

FUNDAMENTAL LENGTH: ℓ_s

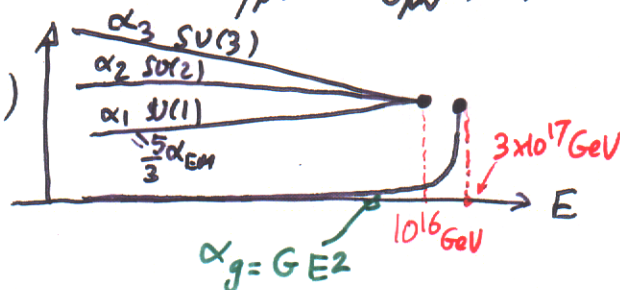
- FINAL THEORY STILL UNDER CONSTRUCTION BUT VERY RICH STRUCTURE, AND MANY DEEP BUILDING BLOCKS UNDERSTOOD

- $D=10$ (OR 11) $\Rightarrow$ INCLUDES KALUZA-KLEIN g_{MN}
 - g_{ab} SCALARS
 - $g_{a\mu}$ VECTORS
 - $g_{\mu\nu}$ TENSOR

- $\rightarrow A_\mu(x)$ GAUGE INTERACTIONS
 - $\rightarrow h_{\mu\nu}(x) = g_{\mu\nu}(x) - \eta_{\mu\nu}$ EINSTEIN'S GRAVITY
- UNIFIES GAUGE THEORIES WITH GRAVITY

"EXPLAINS WHY" $\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$ DYNAMICAL

- UNIFIES ALL INTERACTIONS (?)



- STRINGS $\rightarrow$ "M-BRANES"

$$m=0, 1, 2, 3, \dots$$

$$\int X^\mu(\tau, \sigma)$$

$m=1$
STRING

$$X^\mu(\tau, \sigma_1, \sigma_2)$$

$m=2$
membrane

$$X^\mu(\tau, \sigma_1, \sigma_2, \sigma_3)$$

$m=3$
3-brane
LIKE OUR
(3+1)-WORLD

- MORE GRAVITATIONAL-STRENGTH FIELDS

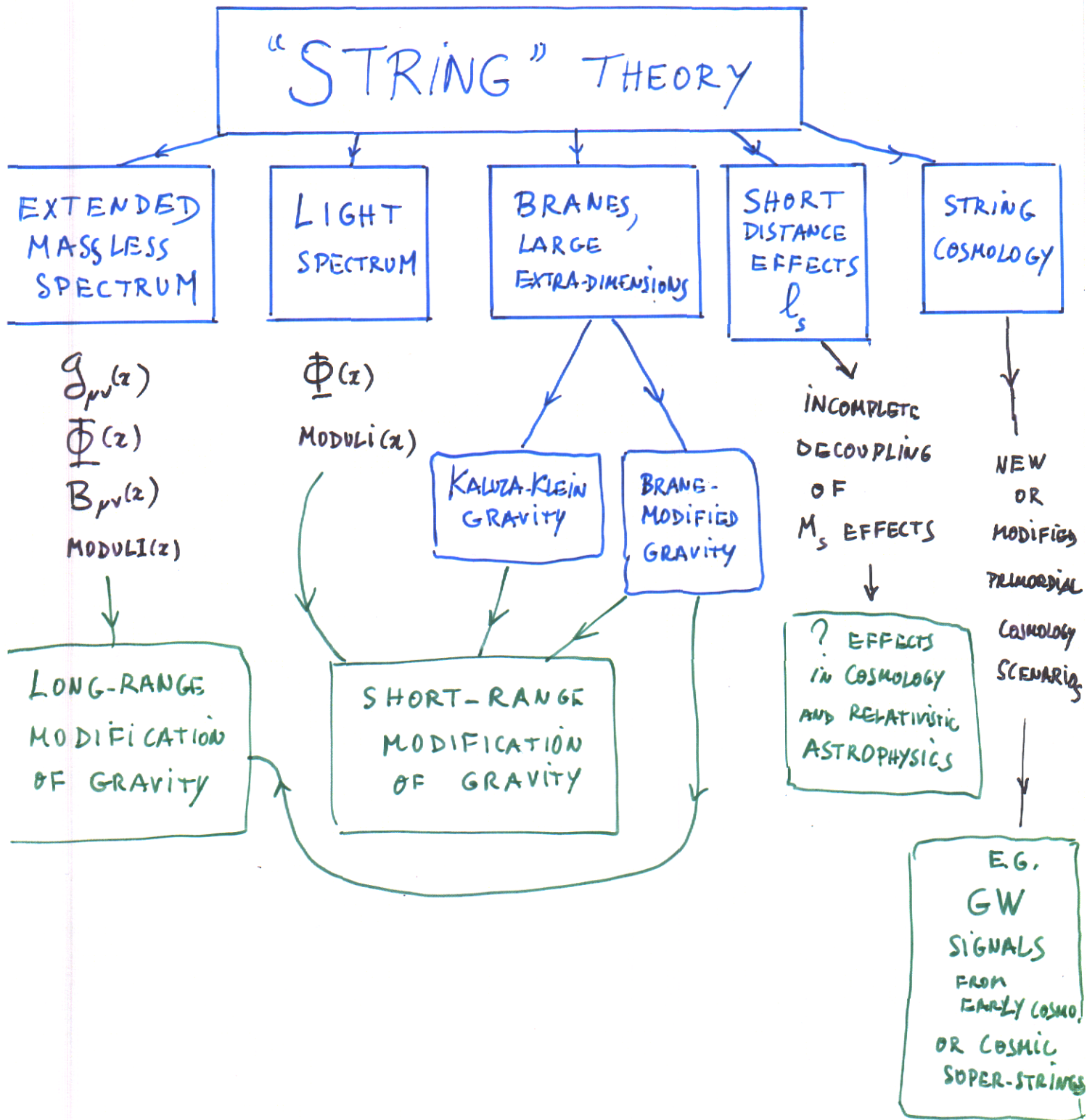
$$\rightarrow g_{\mu\nu}(x) + \Phi(x) + B_{\mu\nu}(x) + \dots$$

CRUCIAL RÔLE $g_s = e^{\langle \Phi \rangle}$

LINKED TO "TORSION" AND, IN CERTAIN LIMIT TO NON-COMMUTATIVITY OF SPACE
 $[x^\mu, x^\nu] = \theta^{\mu\nu}(g, B)$

STRING-INSPIRED PHENOMENOLOGY CV4

- NO CLEAR UNDERSTANDING OF HOW TO FIT OUR WORLD WITHIN STRING THEORY
- ⇒ DISCUSS PHENOMENOLOGICAL POSSIBILITIES; OPEN NEW EXPERIMENTAL OPPORTUNITIES



LOW-ENERGY IMPRINTS OF l_s (l_P) PHYSICS? ^{CV5}

Brout, ...; Jacobson... Brandenberger... B. Greene... Starobinsky... Danielsson... Kaloper...
Burgess... Shenker... Schalm... Porrati... Pullin... Smolin... Ruegg Ellis
Nanopoulos... Amelino-Camelia... Urrutia... Gambini...

VARIOUS PHENOMENOLOGICAL POSSIBILITIES

MODIFIED DISPERSION LAWS: $E^2 = m^2 + p^2 + \beta l_* E^3 + \dots$

BIREFRINGENCE OF VACUUM $\omega_{\pm} = |k| (1 \pm \beta l_* |k| + \dots)$

VIOLATION OF LORENTZ-INVARIANCE ?

DEFORMATION OF LORENTZ-INVARIANCE

QUANTUM DECOHERENCE: PURE STATES $\rightarrow$ MIXED STATES ?

PARTICLE CREATION BY EXPANSION

VARIOUS OBSERVABLE WINDOWS

EXPANSION = MICROSCOPE $\Rightarrow$ POSSIBLE EFFECTS ON CMB's C_l

GRIGSEN-ZATSEPIN-KUZMIN (GZK) THRESHOLD

ULTRA HIGH-ENERGY COSMIC RAYS

γ -RAY BACKGROUND

TIMING OF γ -RAY BURSTS OR ν_s

SYNCHROTRON RADIATION FROM CRAB NEBULA

ROUGH CONCLUSION

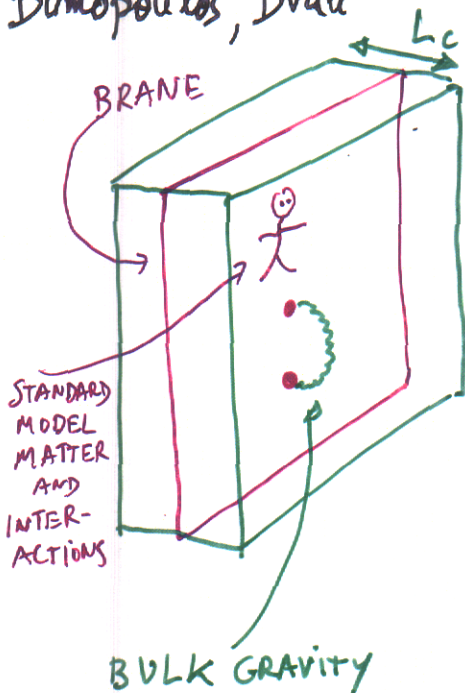
IF EFFECTS $\propto l_*^1 = \frac{1}{M_*^1} \left\{ \begin{array}{l} \cdot \exists \text{ THEORETICAL DIFFICULTIES} \\ \cdot \exists \text{ SEVERE CONSTRAINTS FROM PRESENT DATA} \end{array} \right.$

IF, MORE CONVENTIONALLY, EFFECTS $\propto l_*^2 = \frac{1}{M_*^2} \left\{ \begin{array}{l} \cdot \text{ TOO SMALL TO BE OBSERVED} \end{array} \right.$

BRANES AND GRAVITY

CV6

"LARGE" BUT COMPACT
EXTRA-DIMENSIONS
Antoniadis Arkani-Hamed,
Dimopoulos, Dvali

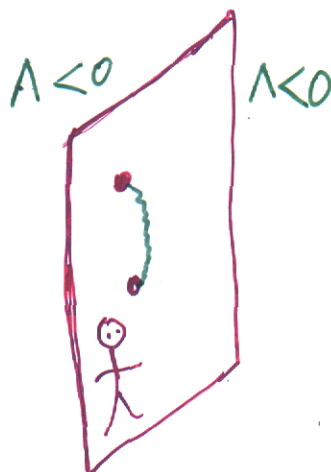


HIGHER-DIMENSIONAL
GRAVITY WHEN

$$r < L_c$$

AND (if $l_s \sim \text{TeV}$)
INTERESTING OBSERVABLE
EFFECTS IN LHC

INFINITE EXTRA-DIMENSIONS
BUT "MISMATCHED" GRAVITY
Randall, Sundrum

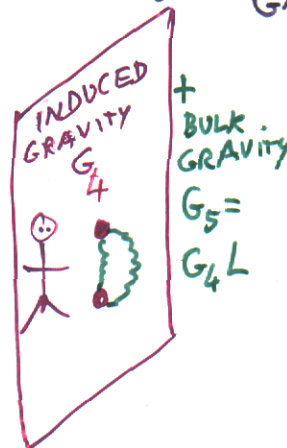


GRAVITY $\approx$
SURFACE WAVE

MODIFICATION OF
GRAVITY WHEN

$$r \lesssim \text{BULK CURVATURE RADIUS} \approx r_c$$

Dvali,
Gabadadze
Porrati



GRAVITY $\approx$
SURFACE $\oplus$ BULK
PROPAGATION

MODIFICATION OF
GRAVITY WHEN

$$r \gtrsim L \equiv \frac{G_5}{G_4}$$

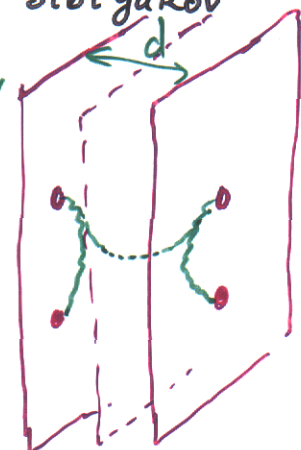
AND SMALL
MODIFICATIONS
FOR $r < L$

Dvali, Gruzinov, Zaldarriaga

$$U' = \frac{GM}{r} \left[1 - \frac{1}{L} \sqrt{\frac{r^3 c^2}{GM}} \right]$$

EFFECTS IN SOLAR-SYSTEM,
LUNAR RANGING...

MULTI-BRANES
Kogan, Mouslopoulas,
Papazoglou, Ross,
Santiago;
Gregory Rubakov,
Sibiryakov



TUNNELLING
(EVANESCENT WAVES)
BETWEEN SEVERAL
GRAVITON WAVES

MULTI-GRAVITY

MODIFICATION OF
GRAVITY BOTH
WHEN

$$r \lesssim r_c$$

AND

$$r \gtrsim r_c e^{d/r_c}$$

BUT PROBLEMS
WITH
"PAULI-FIERZ"
TYPE
MASSIVE GRAVITY

DILATON, MODULI, ... AND VIOLATIONS OF THE EQUIVALENCE PRINCIPLE

EQUIVALENCE PRINCIPLE: $S = \int d^4x \frac{\sqrt{g} R(g)}{16\pi G} + S_{\text{MATTER}}[\psi, A, H; g_{\mu\nu}, \alpha_a, m_a]$

ONLY ONE LONG-RANGE FIELD WITH GRAVIT-STRENGTH COUPLING TO MATTER

ALL COUPLING CONSTANTS ARE THE SAME AS IN SPECIAL RELAT.

? WHY $\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$? WHY $\mu = \frac{m_e}{m_p} \approx \frac{1}{1836}$?

STANDARD MODEL OF PARTICLE PHYSICS: $\exists \sim 20$ ARBITRARY PARAMETERS

IN STRING THEORY, $\exists$ NO DIMENSIONLESS PARAMETERS
 $\exists$ ONLY A DIMENSIONFULL PARAMETER: l_s

ALL DIMENSIONLESS PARAMETERS MUST ARISE AS VACUUM EXPECTATION VALUES OF SOME FIELDS

EG. IN $D=10$, STRING THY CONTAINS A STRING COUPLING CONSTANT g_s

WHOSE VALUE:

$$g_s = \exp \langle \Phi(x) \rangle$$

DILATON = PARTNER OF GRAVITON

IN $D=4$, THERE APPEAR OTHER FIELDS DETERMINING THE VALUES OF THE 4-DIM "CONSTANTS": MODULI FIELDS,
 DETERMINING THE VOLUME AND SHAPE OF COMPACTIFIED DIMENSIONS

AND

$$\alpha = F_\alpha(g_s, \text{MODULI}, \dots)$$

$$G = l_s^2 F_G(g_s, \text{MODULI}, \dots)$$

...

INTUITIVE MEANING OF $g_{\mu\nu}(x) + \Phi(x) + \dots$

	GEOMETRY	COUPLING CONSTANTS	
NEWTON	RIGID	RIGID	
EINSTEIN	SOFT	RIGID	} EINSTEIN EQUIVALENCE PRINCIPLE
STRING Theory	SOFT	SOFT	
			} VIOLATION OF THE EQUIVALENCE PRINCIPLE

g geometry $\sim$ g gravitation $\sim$ g gauge coupling constant $\sim$ G gravitational coupling constant

$$g_{\mu\nu}(x) \sim g^2(x) \sim G(x)$$

BUT THEN ONE WOULD EXPECT:

- NON-UNIVERSALITY OF FREE FALL $\frac{\Delta a}{a} \sim 10^{-5}$

- COSMOLOGICAL VARIATION OF COUPLING CONSTANTS

$$\frac{\dot{\alpha}}{\alpha} \sim \frac{\dot{p}}{p} \sim H_0 \sim 10^{-10} \text{ yr}^{-1}$$

- MODIFICATION OF POST-NEWTONIAN GRAVITY

$$\gamma - 1 \sim \mathcal{O}(1)$$

CONSISTENCY OF DILATON+MODULI $\Phi(z)$ WITH PRESENT EXPERIMENTAL DATA?

CV9

① $m_\Phi \neq 0, V(\Phi) \neq 0$ IN LOW-ENERGY WORLD $\Rightarrow$ ONLY SHORT-RANGE $\propto \frac{e^{-m_\Phi r}}{r}$ EFFECTS

RECENT EXPERIMENTS $\Rightarrow \lambda_\Phi = \frac{1}{m_\Phi} \leq 0.1 \text{ mm} \Rightarrow m_\Phi \geq 10^{-3} \text{ eV}$
 Hoyle...2001
 Chiaverini...2003
 Long...2003

THE VALUE OF m_Φ IS MODEL-DEPENDENT. SOME MODELS NEED TO FIX Φ EARLY ON (BEFORE INFLATION) $\Rightarrow m_\Phi \sim M_s \gg H_{\text{INF}}$

IN SOME MODELS m_Φ IS LINKED TO SUSY BREAKING: $V(\Phi) \sim M_{\text{susy}}^4 \mathcal{V}(\frac{\Phi}{\tilde{m}_P})$
 $\Rightarrow m_\Phi \sim \frac{M_{\text{susy}}^2}{\tilde{m}_P} \sim \frac{(1 \text{ TeV})^2}{2.4 \times 10^{18} \text{ GeV}} \sim 10^{-3} \text{ eV}$
 Taylor, Veneziano '88
 Ferrara et al '94
 Antoniadis et al '97

$\Rightarrow$ POSSIBLE MODIFICATIONS OF CAVENISH EXPERIMENTS JUST BELOW 0.1 mm CURRENT DATA

② $m_\Phi = 0, V(\Phi) \approx 0$, BUT $\exists$ NON-TRIVIAL COUPLING FUNCTIONS $B_i(\Phi)$

$\mathcal{L}_{\text{EFF}} = B_R(\Phi) R(g) + B_\Phi(\Phi) (\nabla\Phi)^2 + B_F(\Phi) F_{\mu\nu}^2 + \dots$ $\downarrow$ $V_{\text{EFF}}(\Phi)$ THROUGH PRESENCE OF MATTER
 IF $\exists \Phi_m; \partial B_i(\Phi_m)/\partial\Phi_m = 0$ Damour, Nordtvedt; Damour, Polyakov

$\exists$ MECHANISM OF NATURAL COSMOLOGICAL ATTRACTION: $\Phi \rightarrow \Phi_m$
 AND Φ NEARLY DECOUPLES FROM MATTER WHEN $\Phi \approx \Phi_m$

$\Rightarrow$ NATURALLY SUPPRESSED MODIFICATIONS OF LONG-RANGE GRAVITY

③ BOTH A QUINTESSENCE-LIKE $V(\Phi) \neq 0$ AND COUPLING TO MATTER $B(\Phi)$

$\Rightarrow m_\Phi$ DEPENDS ON SURROUNDING MATTER DENSITY, SO THAT Φ IS SHORT-RANGED IN EARTH-BOUND EXPTS Khoury, Willman, Brax, ...

DILATON RUN-AWAY SCENARIO

CV10

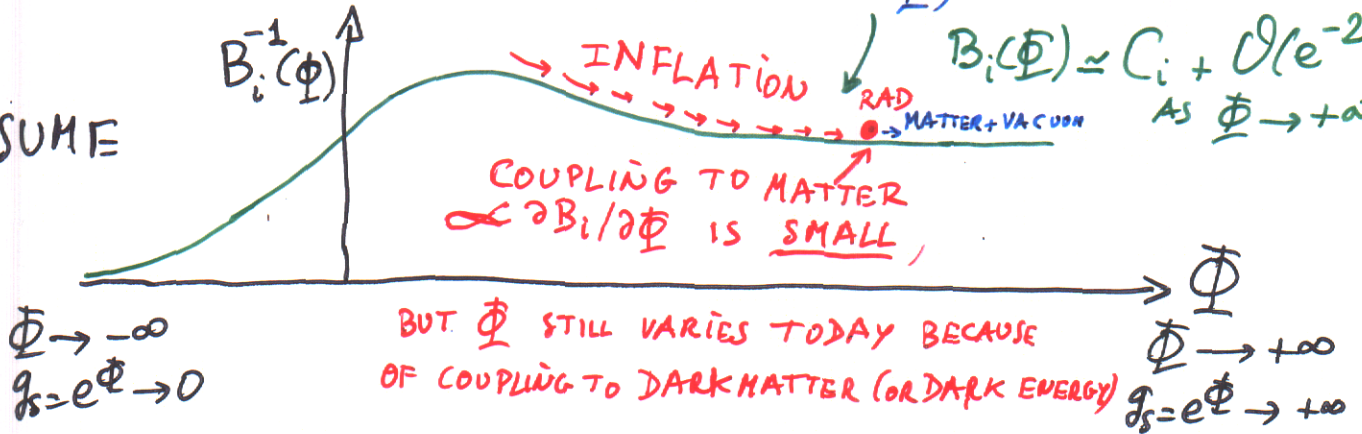
(Damour, Piazza, Veneziano)

$$\mathcal{L}_{\text{EFF}} = B_R(\Phi) R(g) + B_\Phi(\Phi) (\partial\Phi)^2 + B_F(\Phi) F_{\mu\nu}^2 + \dots$$

DILATON COUPLING FUNCTIONS $B_i(\Phi)$

$$B_i(\Phi) \simeq C_i + \mathcal{O}(e^{-2\Phi}) \quad \text{As } \Phi \rightarrow +\infty$$

ASSUME



OBSERVATIONAL CONSEQUENCES TODAY

ASSUME INFLATIONARY POTENTIAL: $V(\chi) = \lambda(\Phi) \chi^n$ WITH $n=2$

WEAK
EQUIVALENCE
PRINCIPLE
VIOLATION

$$\frac{\Delta a}{a} \sim 5 \times 10^{-4} \left(\frac{b_F}{b_{\lambda C}} \right)^2 \left(\frac{\delta \rho}{\rho} \right)^2 \sim \left(\frac{b_F}{b_{\lambda C}} \right)^2 \times 10^{-12}$$

DENSITY FLUCTUATIONS
DIMENSIONLESS PARAMETERS (FROM INFLATION): $\frac{\delta \rho}{\rho} \sim 5 \times 10^{-5}$

VARIATION
OF CONSTANTS

$$\alpha_{\text{EM}} = \frac{e^2}{\hbar c}, \dots$$

$$\frac{d \ln \alpha_{\text{EM}}}{dt} \sim \pm 10^{-16} \sqrt{1 + q_0 - \frac{3\Omega_m}{2}} \sqrt{10^{12} \frac{\Delta a}{a}} \text{ yr}^{-1}$$

COUPLING TO DARK MATTER
OR DARK ENERGY

$$\frac{\Omega_m \alpha_m + 4 \Omega_v \alpha_v}{\Omega_m + 2 \Omega_v}$$

COUPLING TO
ORDINARY MATTER

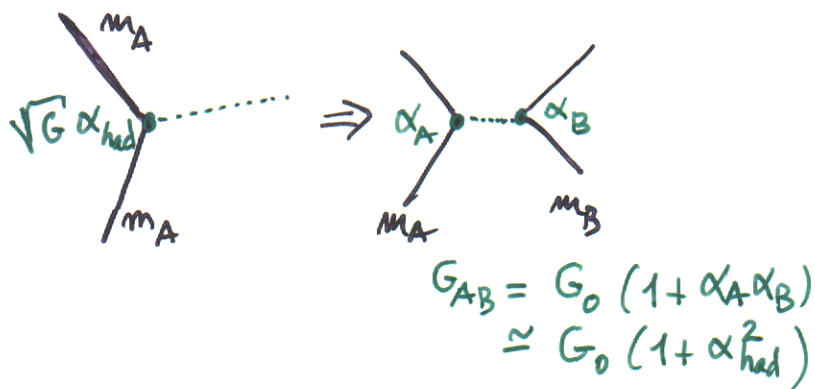
$\propto \text{had}$

CORRELATED EFFECTS LINKED TO EQUIV. PRINCIPLE VIOLATIONS

CV11

IF $\exists$ ULTRA-LIGHT "DILATON-LIKE", OR "MODULI-LIKE" FIELD ϕ

COUPLED TO HADRONIC (GLUONIC) MATTER WITH STRENGTH α_{had}



$$G_{AB} = G_0 (1 + \alpha_A \alpha_B) \approx G_0 (1 + \alpha_{had}^2)$$

POST-NEWTONIAN EFFECTS $\gamma-1, \beta-1$
WEAK EQUIV. PRINCIPLE VIOLATIONS $\frac{\Delta a}{a}$
VARIATION OF CONSTANTS $\dot{\alpha}/\alpha, \dot{\mu}/\mu$
DIFFERENTIAL VARIATION OF CLOCK RATES $\frac{\partial}{\partial \nu} \ln \alpha, \dots$

ARE ALL PROPORTIONAL TO α_{had}^2

EG:

$$\gamma-1 = -2 \frac{\alpha_{had}^2}{1 + \alpha_{had}^2} \approx -2 \alpha_{had}^2$$

$$\beta-1 \approx \frac{1}{2} \frac{\partial \alpha_{had}}{\partial \phi} \alpha_{had}^2$$



$$\left(\frac{\Delta a}{a} \right)_{AB} \approx 2 \times 10^{-5} \alpha_{had}^2 \left[\Delta \left(\frac{E}{M} \right)_{AB} + c_B \Delta \left(\frac{B}{M} \right)_{AB} + c_D \Delta \left(\frac{D}{M} \right)_{AB} \right]$$

$$E \equiv \frac{Z(Z-1)}{(N+Z)^{1/3}}$$

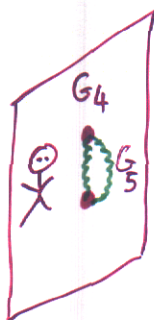
$$B = N+Z$$

$$D = N-Z$$

RESTRICTED DEPENDENCE ON A AND B

$\Rightarrow$ PRESENT $\frac{\Delta a}{a} \lesssim 10^{-12}$ ALREADY CORRESPOND TO $|\gamma-1| \sim \alpha_{had}^2 \sim 10^{-7}$

SOME POSSIBLE LONG-RANGE MODIFICATIONS OF GRAVITY CV12



- BRANE-INDUCED + BULK GRAVITY (Dvali, Gabadadze, Porrati)

$$L = \frac{G_5}{G_4}$$

- NO VIOLATION OF EQUIVALENCE PRINCIPLE
 - IF $L \sim ct_0 \sim \text{HUBBLE}^{-1}$, MIGHT EXPLAIN THE "ACCELERATION OF EXPANSION"
 - SMALL FRACTIONAL DEVIATIONS $\sim \frac{1}{L} \sqrt{\frac{r^3 c^2}{GM}}$ FROM EINSTEIN ON ORDINARY SCALES
- ? BEST TESTABLE IN LUNAR RANGING ?

- TENSOR-SCALAR GRAVITY, $g_{\mu\nu} \oplus \phi$, WITH BOTH $V(\phi)$ AND $g_{\mu\nu}^A = B_A(\phi) g_{\mu\nu}$ (Khoury, Weltman)
- CAN INCORPORATE EP VIOLATION
- POSSIBLY SIGNIFICANT MODIFICATIONS OF GRAVITY IN SPACE VS EARTH-BOUND

- TENSOR $g_{\mu\nu}$ + OTHER FIELDS: EG. $B_{(\mu\nu)}$ (Einstein, T.D., Deser, McCarthy, Moffat)
- NECESSARILY INCORPORATES EP VIOLATION
- CONTAINS MASSIVE VECTOR INTERACTIONS

CONCLUSIONS

THE NEW GRAVITY FRONTIER

- UP TO THE END OF THE 1980's, ONE CONSIDERED ONLY FEW, NATURAL MODIFICATIONS OF EINSTEIN'S GRAVITY (JORDAN-FIERZ-BRANS-DICKE), [OR QUITE ARTIFICIAL, UNMOTIVATED ALTERNATIVE THEORIES]
- RECENTLY, A BETTER UNDERSTANDING OF THE RICH STRUCTURE OF STRING THEORY (DILATON, ..., BRANES, ..., LARGE DIMENSIONS, ..., WARPED COMPACTIFICATIONS...) HAS MOTIVATED THE CONSIDERATION OF MANY NEW TYPES OF MODIFICATIONS OF GR
 - SHORT-RANGE MODIFICATIONS : $< 0.1 \text{ mm}$
 - LONG-RANGE MODIFICATIONS
- IN ADDITION, RECENT OBSERVATIONAL DISCOVERIES SUGGEST THAT OUR CURRENT THEORETICAL GRAVITY FRAMEWORK MIGHT BE INCOMPLETE OVER LONG DISTANCES / TIMES :
 - "DARK MATTER" IN GALAXIES, HALOS OF GAL. AND LSS
 - "ACCELERATED EXPANSION", AND "DARK ENERGY"
- ? + PIONEER 10, 11 "ANOMALOUS" ACCELERATION
 $a \approx 9 \times 10^{-8} \text{ cm/s}^2 \approx c H_0$, BUT CANNOT BE UNIVERSAL (? EP)
~~NO~~ NO CONVINCING THEORETICAL MODEL
- ? + SOME CLAIMS OF VARIATION OF CONSTANTS (Webb...; Petitjean...)
- ~~NO~~ NO HARD PREDICTIONS OR WELL-DEFINED TARGETS, BUT ONLY CONSEQUENCES OF GENERAL STRUCTURES : EG. IN STRING THEORY ALL COUPLING CONSTANTS ARE FIELDS $\Rightarrow$ EXPECT SOME EQUIVALENCE PRINCIPLE VIOLATION AT SOME LEVEL.
- BUT, $\exists$ "EXISTENCE PROOFS" (MODELS) THAT NEW INTERACTIONS COULD MODIFY EINSTEIN/NEWTON GRAVITY JUST BELOW CURRENT TESTS.

EG RUN-AWAY DILATON $\Rightarrow$ CORRELATED EFFECTS

$$\frac{\delta \rho}{\rho} \sim 5 \times 10^{-5} ; \quad \frac{\Delta a}{a} \lesssim 10^{-12} ; \quad \gamma - 1 \sim 10^{-7} ; \quad \frac{\dot{\alpha}_{\text{EM}}}{\alpha_{\text{EM}}} \sim 10^{-16} \text{ yr}^{-1}$$

CONSTRAINTS ON $\alpha_0^2 \equiv \alpha_{\text{hadron}}^2$ FROM PRESENT AND FUTURE EXPERIMENTS [LONG-RANGE DEVIATIONS]

COMPOSITION-INDEPENDENT

LIGO/VIRGO

PRESENT SOLAR SYSTEM EXPTS
BINARY PULSAR EXPTS

PRESENT VLBI TESTS $\Delta\theta_\odot$

CASSINI
GPB

PARCSEC ASTROMETRY
POINTS

GAIA

TIME DELAY FROM LASER LINKS
TO HELIOCENTRIC CLOCKS

SORT

LATOR

COMPOSITION-DEPENDENT

α_{had}^2

OKLO

* USING
 $\left(\frac{\delta\nu}{\nu}\right)_{\text{EFFECTIVE}} \sim 10^{-17}$

GROUND CLOCK (DIFFERENTIAL)*

GEOCENTRIC CLOCK (DIFFERENTIAL)*

PRESENT EP EXPTS

WEBB ET AL. $(\Delta\alpha/\alpha)_{z \sim 1} \sim 10^{-5}$

SPACETIME

ULTIMATE
HELIOCENTRIC CLOCK (DIFFERENTIAL)*

USCOPE

STEP

NEWTON

