PAVIA
29 MARCH - 1 APRIL
2005

WAS EINSTEIN 100% RIGHT ?

Thibault Damour
IHES

GENERAL RELATIVITY

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

  Λ: COSMOLOGICAL CONSTANT

  $g_{\mu\nu}$: EQUIVALENCE PRINCIPLE

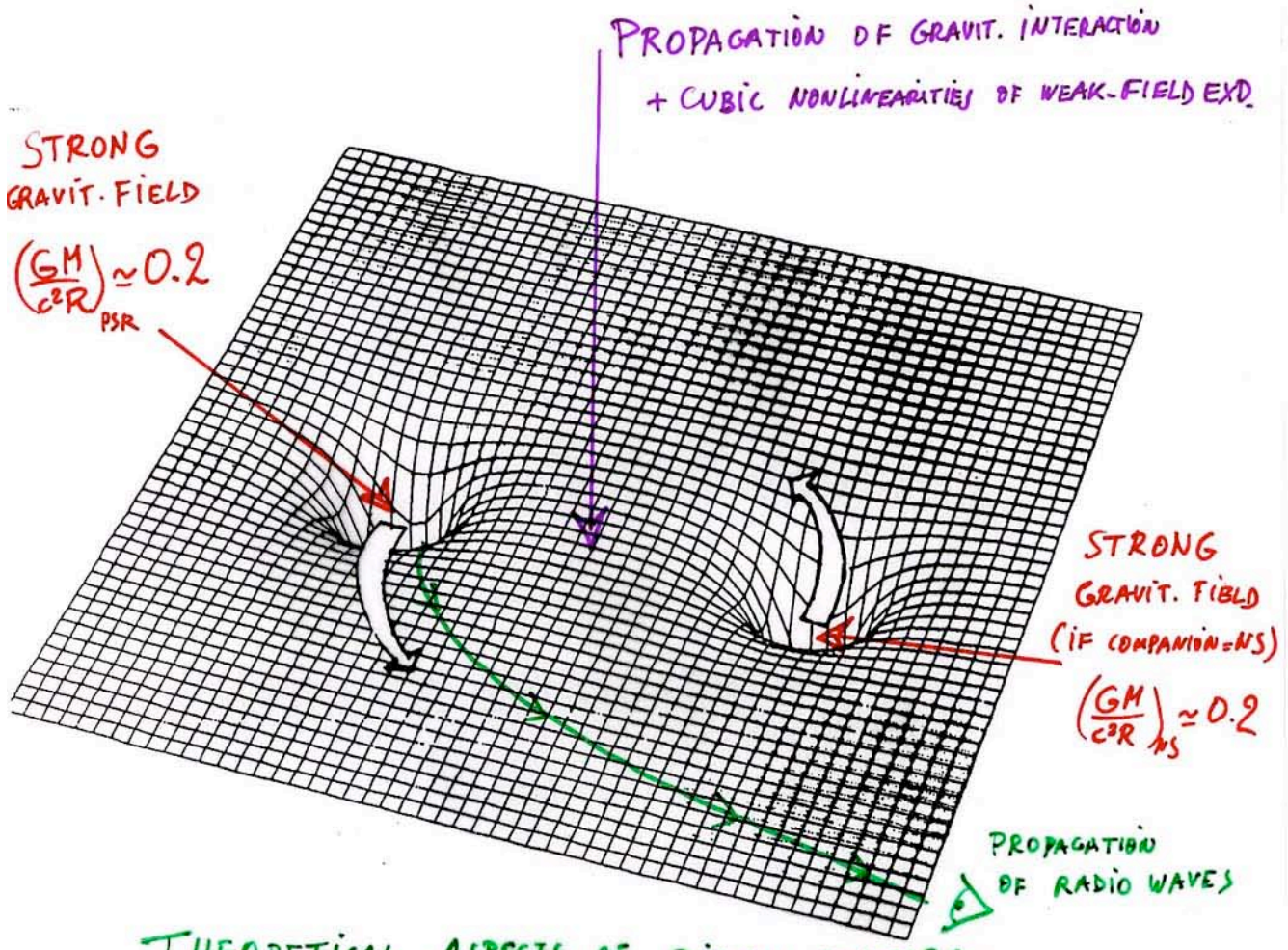
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

EXPERIMENTAL CONFIRMATIONS

- EQUIVALENCE PRINCIPLE TESTS
  $$\left(\frac{\Delta a}{a}\right)_{Be\,Cu} = (-1.9 \pm 2.5) \times 10^{-12}$$
  $$\left|\frac{\alpha^{Okl_o} - \alpha^{Now}}{\alpha}\right| \lesssim 10^{-7}$$
- 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: 4 INDEPENDENT CONFIRMATIONS OF REALITY OF GRAV. RADIATION ; $\sim 10^{-3}$
  - 2+1+3 = 6 CONFIRMATIONS OF G.R. STRONG-FIELD REGIME ; $\sim 10^{-2}$
  - PSR J0407+1607, PSR J2016+1947: ≥ 2 SEP TESTS ; $\sim 10^{-3}$

BINARY PULSARS: FIRST POSSIBILITY OF PROBING THE FULL STRUCTURE OF RELATIVISTIC GRAVITY

- RADIATIVE EFFECTS [FIELD PROPAGATION]
- HIGHLY NON-LINEAR EFFECTS [SRONG FIELDS]



THEORETICAL ASPECTS OF BINARY PULSARS:

(1) MOTION OF TWO STRONGLY SELF-GRAVITATING BODIES
(T.D. & DERUELLE '81 , T.D. 82, 83)

(2) RELATIVISTIC TIMING OF A BINARY PULSAR
(BLANDFORD, TEUKOLSKY '76 , T.D. & DERUELLE '85, 86)

(3) USE OF BINARY PULSARS AS PROBES OF RELATIVISTIC GRAVITY
(EARDLEY '75 , WILL, EARDLEY '77 , T.D. '88, T.D. & TAYLOR '92)

(V/c)^5 EQUATIONS OF MOTION IN GENERAL RELATIVITY G6

accelerations. Then each body must satisfy the following equation of motion (Damour and Deruelle, 1981*a*; Damour, 1982):

$$a^i = A_0^i(\vec{z}-\vec{z}') + c^{-2}A_2^i(\vec{z}-\vec{z}', \vec{v}, \vec{v}') + c^{-4}A_4^i(\vec{z}-\vec{z}', \vec{v}, \vec{v}', \vec{S}, \vec{S}') + c^{-5}A_5^i(\vec{z}-\vec{z}', \vec{v}-\vec{v}') + O(c^{-6}), \quad (154)$$

with

$$A_0^i = -Gm'R^{-2}N^i, \quad (155)$$

$$A_2^i = Gm'R^{-2}\{N^i[-v^2-2v'^2+4(vv')+\tfrac{3}{2}(Nv')^2+5(Gm/R)+4(Gm'/R)] + (v^i-v'^i)[4(Nv)-3(Nv')]\}, \quad (156)$$

$$A_4^i = B_4^i + C_4^i + D_4^i, \quad (157)$$

$$B_4^i = Gm'R^{-2}\{N^i[-2v'^4+4v'^2(vv')-2(vv')^2+\tfrac{3}{2}v^2(Nv')^2+\tfrac{9}{2}v'^2(Nv')^2 - 6(vv')(Nv')^2-\tfrac{15}{8}(Nv')^4+(Gm/R)(-\tfrac{15}{4}v^2+\tfrac{5}{4}v'^2-\tfrac{5}{2}(vv')+\tfrac{39}{2}(Nv)^2 - 39(Nv)(Nv')+\tfrac{17}{2}(Nv')^2)+(Gm'/R)(4v'^2-8(vv')+2(Nv)^2 - 4(Nv)(Nv')-6(Nv')^2)] + (v^i-v'^i)[v^2(Nv')+4v'^2(Nv)-5v'^2(Nv')-4(vv')(Nv) + 4(vv')(Nv')-6(Nv)(Nv')^2+\tfrac{9}{2}(Nv')^3 + (Gm/R)(-\tfrac{63}{4}(Nv)+\tfrac{55}{4}(Nv'))+(Gm'/R)(-2(Nv)-2(Nv'))]\}, \quad (158)$$

$$C_4^i = G^3m'R^{-4}N^i[-\tfrac{57}{4}m^2-9m'^2-\tfrac{69}{2}mm'], \quad (159)$$

$$D_4^i = \left(\frac{S^{ik}}{m}+2\frac{S'^{ik}}{m'}\right)(v^l-v'^l)\left(\frac{Gm'}{R}\right)_{,kl} + \left(2\frac{S^{kl}}{m}+2\frac{S'^{kl}}{m'}\right)(v^l-v'^l)\left(\frac{Gm'}{R}\right)_{,ik}, \quad (160)$$

and

$$A_5^i = \tfrac{4}{5}G^2mm'R^{-3}\{V^i[-V^2+2(Gm/R)-8(Gm'/R)] + N^i(NV)[3V^2-6(Gm/R)+\tfrac{52}{3}(Gm'/R)]\}. \quad (161)$$

The two parameters m and m' appearing in eqs. (154)–(161) are the 'Schwarzschild masses' of the condensed bodies. They are two constants which appear in the external gravitational field, in which are hidden many internal structure effects (see the discussion of the 'effacement of internal structure' in Section 6.14). On the other hand, the spin tensors undergo a slow evolution (on the post-Newtonian time scale, i.e. β_c^{-2} times the orbital period) which is also obtained in the Einstein–Infeld–Hoffmann–Kerr-type approach (Damour, 1982, and references therein). Introducing, *à la* Schiff, a suitable spin-vector, $\vec{S}$, associated with $S_{\mu\nu}$, the law of evolution ('spin precession') reads for the first body (see also references in Section 6.13.2)

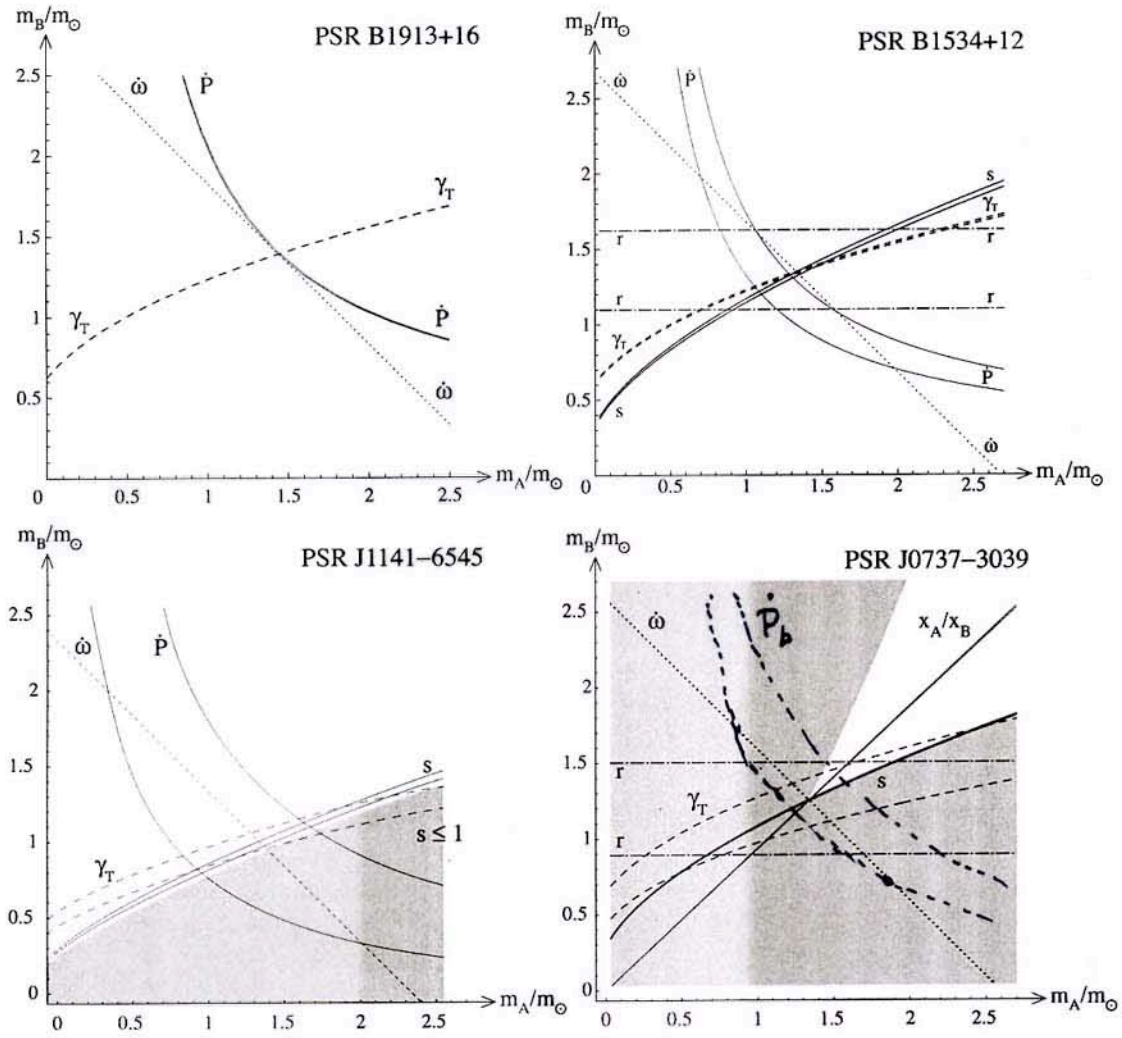
$$\frac{d\vec{S}}{dt} = \left[\frac{Gm'}{c^2R^2}\vec{N}\times\left(\frac{3}{2}\vec{v}-2\vec{v}'\right)\right]\times\vec{S}+O\left(\frac{1}{c^4}\right). \quad (162)$$

"DRESSED MASSES" INCORPORATING STRONG-SELF-FIELD EFFECTS

GRAVITATIONAL RADIATION DAMPING

DIRECT EFFECT OF PROPAGATION OF GRAVITY AT SPEED C

T6


PSR B1913+16
PSR B1534+12
PSR J1141−6545
PSR J0737−3039
$m_B/m_\odot$
$m_A/m_\odot$
$\dot{\omega}$
$\dot{P}$
γ_T
r
s
$s \leq 1$
$\dot{P}_b$
x_A/x_B

FIRST APPROACH TO THEORY-DEPENDENT ANALYSIS

IDEA : GENERALIZE PARAMETRIZED POST NEWTONIAN FRAMEWORK
(Eddington '24, Schiff '60, Baierlein '67, Nordtvedt '68, Will '71)

SOLAR SYSTEM ⇒ WEAK FIELD $\frac{GM}{c^2 r} \lesssim 10^{-6} \ll 1$

MAIN FIRST-ORDER CORRECTIONS PARAMETRIZED BY :

$$\bar{\gamma} \equiv \gamma^{PPN} - 1 \quad : \text{LIGHT DEFLEXION}$$

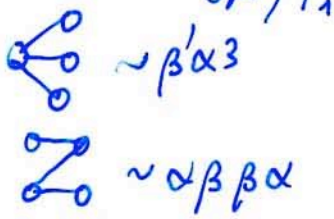
$$\bar{\beta} \equiv \beta^{PPN} - 1 \quad : \text{PERIASTRON PRECESSION}$$

? GENERALIZATION OF $\bar{\beta}$ AND $\bar{\gamma}$ TO SECOND-ORDER CORRECTIONS $\propto \left(\frac{GM}{c^2 r}\right)^2$?

SEEK INSPIRATION FROM SIMPLEST CLASS OF THEORIES : TENSOR-SCALAR $g_{\mu\nu}, \varphi_1, \varphi_2 \ldots$

SECOND-ORDER (2PN) CORRECTIONS PARAMETRIZED BY ONLY TWO PARAMETERS
(Damour, Esposito-Farèse '96)

$$\epsilon, \quad \zeta$$



E.G.
EFFECTIVE GRAVITATIONAL COUPLING BETWEEN A and B

1PN (Nordtvedt '68)

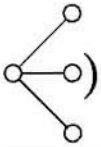
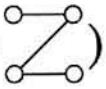
$$\frac{G_{AB}}{G} = 1 + (4\bar{\beta} - \bar{\gamma})\left(\frac{E_A^{grav}}{m_A c^2} + \frac{E_B^{grav}}{m_B c^2}\right)$$

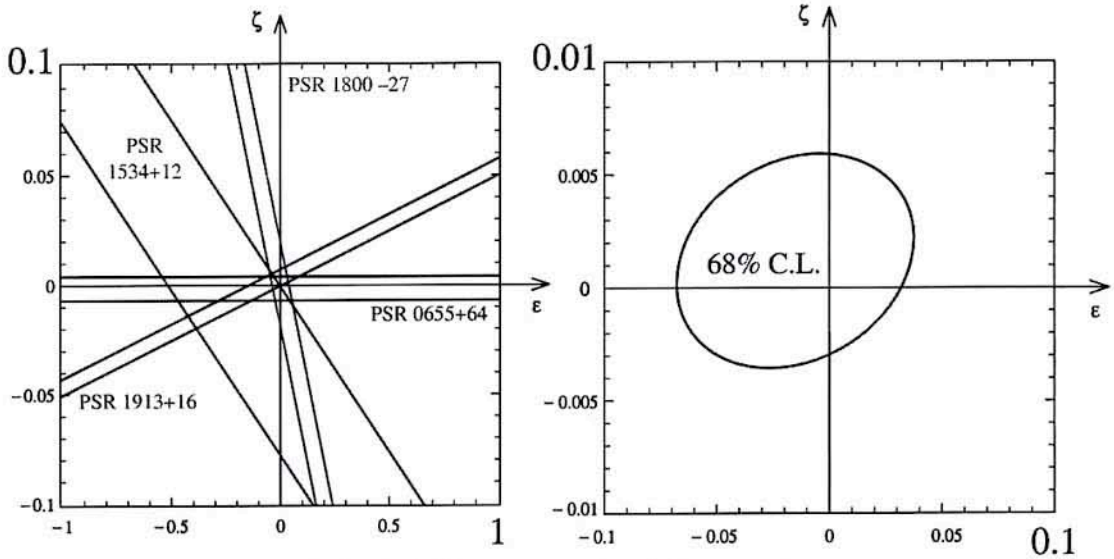
2PN (Damour, Esposito-Farèse '96)

$$+ 4\zeta \left(\frac{E_A^{grav}}{m_A c^2}\right)\left(\frac{E_B^{grav}}{m_B c^2}\right) + \left(\frac{\epsilon}{2} + \zeta\right)\frac{\langle U^2\rangle_A + \langle U^2\rangle_B}{c^4} + \ldots$$

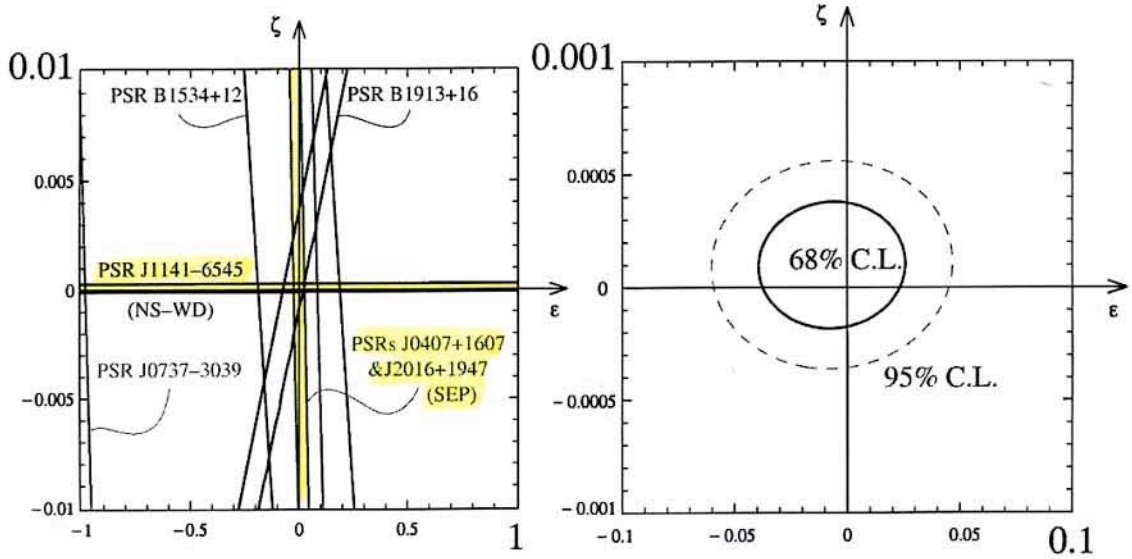
- 2PN TERMS, $\propto \epsilon, \zeta$, ARE TOO SMALL TO BE MEASURABLE IN SOLAR SYSTEM [THEY DO NOT ENTER LIGHT DEFLECTION !]
- BINARY PULSARS : $\frac{E_A^{grav}}{m_A c^2} \simeq 0.15$ ⇒ ANALYZE DATA AS CONSTRAINTS ON ϵ, ζ

Binary pulsar constraints on the 2PN parameters

ε ($\propto$ ) and ζ ($\propto$ )



[Damour & Esposito-Farèse, PRD **53** (1996) 5541]



situation in 2004 [T.D. & G.E-F, in preparation]

$\Rightarrow$ 2× tighter constraints on ε ; 15× tighter constraints on ζ

$-4\times10^{-2} < \varepsilon < 3\times10^{-2}$ $\quad -2\times10^{-4} < \zeta < +4\times10^{-4}$

BEYOND GENERAL RELATIVITY

CV2

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

- EFFECTS OF $\hbar \neq 0$

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

  $\langle 2|T^{MATT}_{\mu\nu}|2\rangle = -g_{\mu\nu}\left\{ \sum_a \pm \int_0^{\omega_c} \frac{\hbar}{2} \sqrt{m_a^2 + \vec{k}^2}\, \frac{d^3k}{(2\pi)^3} \right\} + T^{EXCITATIONS}_{\mu\nu}$

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

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

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

- WHY $\exists$ DIFFERENT TYPES OF INTERACTIONS ?
  - ELECTROMAGNETIC, WEAK INT., STRONG INT. — GAUGE THEORIES A^a_μ
  - GRAVITY $g_{\mu\nu}$

- WHY $\exists$ SEVERAL HIERARCHIES
  - COSMOLOGICAL $L_0 = c t_0 \sim 10^{28}$ cm $\gg\gg$ ANY $L_{PARTICLE}$
  - PARTICLE $M_{EW} \sim 250\,GeV \ll M_{GAUGE\ UNIF} \sim 10^{16}\,GeV$ OR $M_P \sim 10^{19}\,GeV$
  - COSMOL. CONSTANT $\rho^{THY}_{VAC} \sim \omega_c^4 + m^2\omega_c^2 + m^4 + \dots \gg\gg \rho^{OBS}_{VAC} \sim (10^{-3}\,eV)^4$

STRING THEORY

- ONLY CONCRETE PHYSICAL FRAMEWORK TO DISCUSS QUANTUM GR.
- STARTING POINT:

$\bullet \longrightarrow$ OR $\quad X^\mu(\tau) \qquad X^\mu(\tau,\sigma)$

QUANTUM MECHANICS: $\hbar$

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

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

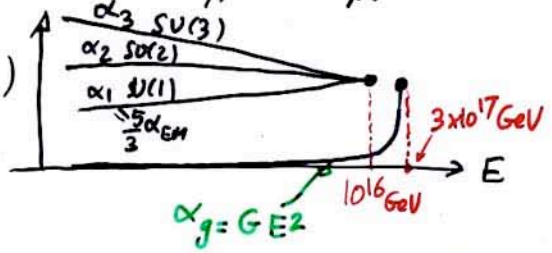
$$d^2A = \sqrt{(\dot X^\mu X'_\mu)^2 - (\dot X^\mu)^2 (X'^\mu)^2}$$

FUNDAMENTAL LENGTH: ℓ_s

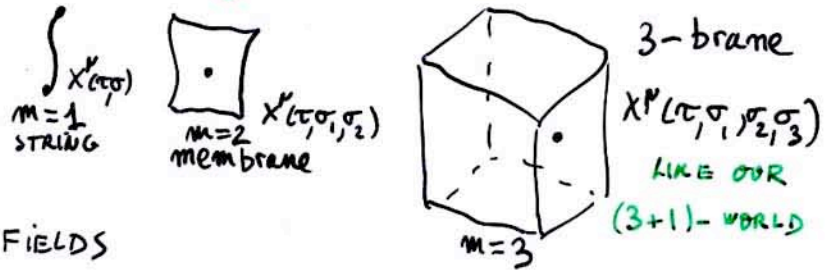
- FINAL THEORY STILL UNDER CONSTRUCTION
  BUT VERY RICH STRUCTURE, AND MANY DEEP BUILDING BLOCKS UNDERSTOOD
- $D = 10$ (OR 11) $\Rightarrow$ INCLUDES KALUZA-KLEIN g_{MN}
  - g_{ab} SCALARS
  - $g_{a\mu}$ VECTORS
  - $g_{\mu\nu}$ TENSOR
- $\longrightarrow A_\mu(x)$ GAUGE INTERACTIONS
  $\longrightarrow h_{\mu\nu}(x) = g_{\mu\nu}(x) - \eta_{\mu\nu}$ EINSTEIN'S GRAVITY
  } UNIFIES GAUGE THEORIES WITH GRAVITY

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

- UNIFIES ALL INTERACTIONS (?)



- STRINGS $\to$ "m-BRANES"
  $m = 0, 1, 2, 3, \dots$



- MORE GRAVITATIONAL-STRENGTH FIELDS

$\longrightarrow g_{(\mu\nu)}(x) + \underbrace{\Phi(x)}_{\text{DILATON}} + B_{[\mu\nu]}(x) + \dots$

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

LINKED TO "TORSION", AND IN CERTAIN LIMIT TO NON-COMMUTATIVITY OF SPACE

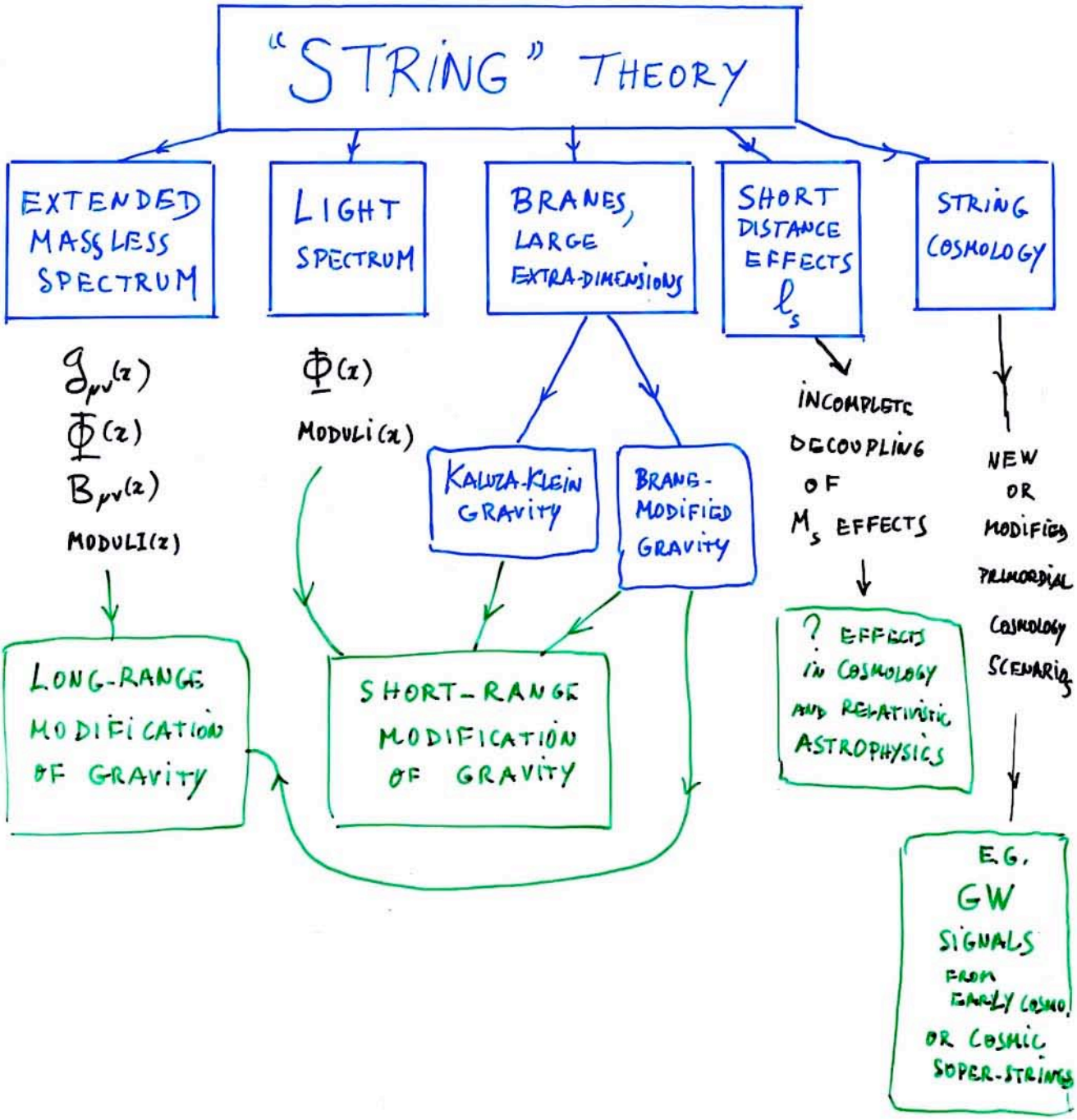
$[x^\mu, x^\nu] = \theta^{\mu\nu}(g, B)$

STRING-INSPIRED PHENOMENOLOGY

CV4

- NO CLEAR UNDERSTANDING OF HOW TO FIT OUR WORLD WITHIN STRING TH.

⇒ DISCUSS PHENOMENOLOGICAL POSSIBILITIES ; OPEN NEW EXPERIMENTAL OPPORTUNITIES

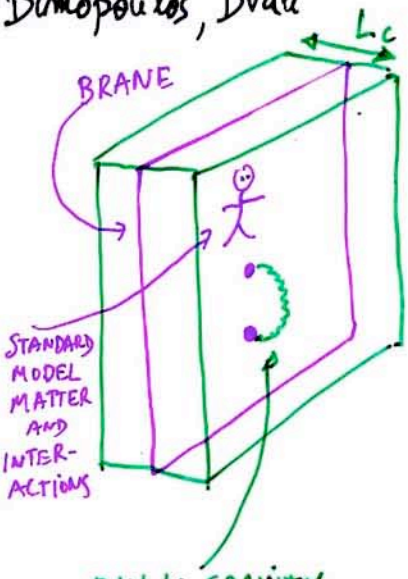


BRANES AND GRAVITY

CV6

"LARGE" BUT COMPACT EXTRA-DIMENSIONS

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali



⇓

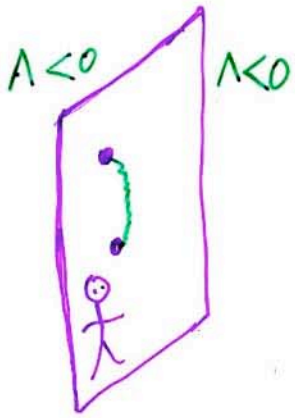
HIGHER-DIMENSIONAL GRAVITY WHEN

$r < L_c$

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

INFINITE EXTRA-DIMENSIONS BUT "MISMATCHED" GRAVITY

Randall, Sundrum



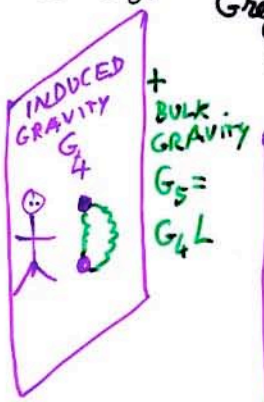
GRAVITY ≃ SURFACE WAVE

⇓

MODIFICATION OF GRAVITY WHEN

$r \lesssim$ BULK CURVATURE RADIUS $\equiv r_c$

Dvali, Gabadadze, Porrati



GRAVITY = SURFACE ⊕ BULK PROPAGATION

⇓

MODIFICATION OF GRAVITY WHEN

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

AND SMALL MODIFICATIONS FOR $r < L$

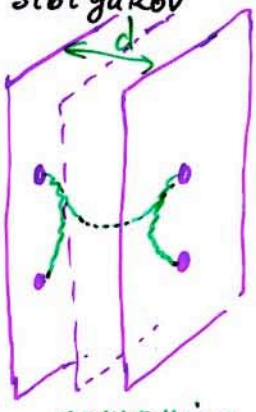
Dvali, Gruzinov, Zaldarriaga

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

EFFECTS IN SOLAR-SYSTEM, LUNAR RANGING...

MULTI-BRANES

Kogan, Mouslopoulos, Papazoglou, Ross, Santiago; Gregory, Rubakov, Sibiyakov



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

$g_{\mu\nu}$: ONLY ONE LONG-RANGE FIELD WITH GRAVIT.-STRENGTH COUPLING TO MATTER

α_a, m_a : ALL COUPLING CONSTANTS ARE THE SAME AS IN SPECIAL RELAT.

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

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 : $\boxed{g_s = \exp \langle \Phi(x) \rangle}$

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

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

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

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

$$\underset{\text{geometry}}{g} \sim \underset{\text{gravitation}}{g} \sim \underset{\substack{\text{gauge}\\ \text{coupling}\\ \text{constant}}}{g} \sim \underset{\substack{\text{gravitational}\\ \text{coupling}\\ \text{constant}}}{G}$$

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

BUT THEN ONE WOULD EXPECT:

- NON-UNIVERSALITY OF FREE FALL $\quad \frac{\Delta a}{a} \sim 10^{-5}$
- COSMOLOGICAL VARIATION OF COUPLING CONSTANTS

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

- MODIFICATION OF POST-NEWTONIAN GRAVITY

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

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

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

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

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

IN SOME MODELS m_Φ IS LINKED TO SUSY BREAKING: $V(\Phi) \sim M_{SUSY}^4\, \mathcal{V}\left(\frac{\Phi}{M_P}\right)$

$\Rightarrow m_\Phi \sim \frac{m_{SUSY}^2}{M_P} \overset{?}{\sim} \frac{(1\ TeV)^2}{2.4\times 10^{18}\ GeV} \sim 10^{-3}\ eV$

Taylor, Veneziano '88
Ferrara et al '94
Antoniadis et al '97

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

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

$\mathcal{L}_{EFF} = B_R(\Phi) R(g) + B_\Phi(\Phi)(\nabla\Phi)^2 + B_F(\Phi) F_{\mu\nu}^2 + \cdots$ $\Rightarrow$ $V_{EFF}(\Phi)$ THROUGH PRESENCE OF MATTER

Damour, Nordtvedt ; Damour, Polyakov

IF $\exists\ \Phi_m$; $\partial B_i(\Phi_m)/\partial \Phi_m = 0$

- $\exists$ MECHANISM OF NATURAL COSMOLOGICAL ATTRACTION: $\Phi \to \Phi_m$ AND Φ NEARLY DECOUPLES FROM MATTER WHEN $\Phi \simeq \Phi_m$

$\Rightarrow$ 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, Weltman, Brax, ...

INVERSE-SQUARE LAW TESTS (Adelberger, Heckel, Nelson 103)

$$V(r) = -\frac{G m_1 m_2}{r}\left[1 + \alpha e^{-\frac{r}{\lambda}}\right]$$

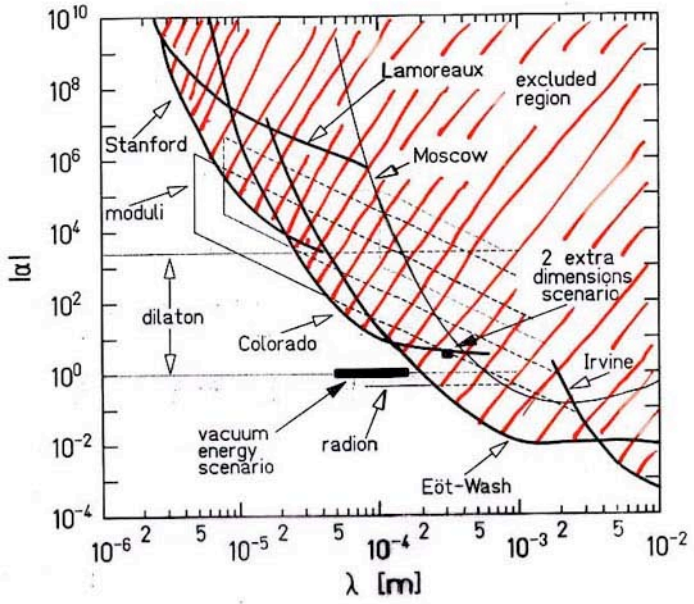


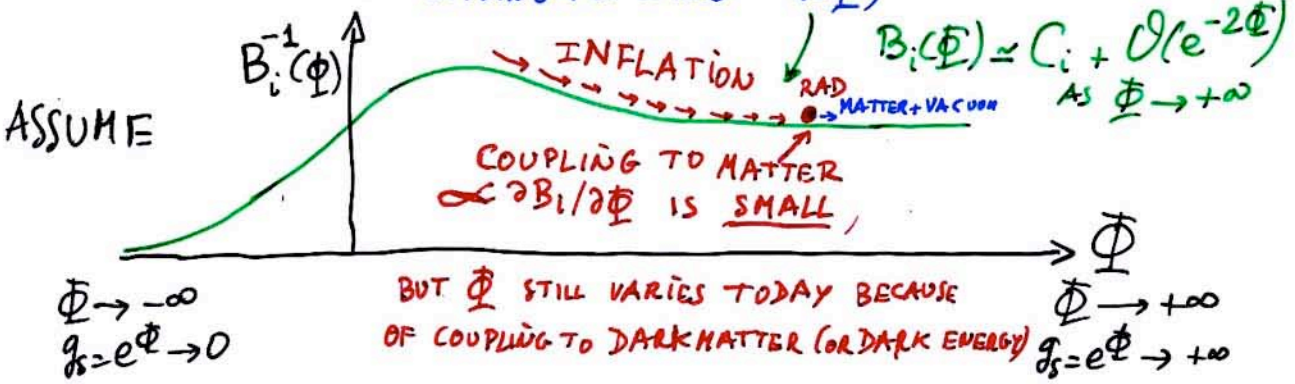
Figure 5: 95%-confidence-level constraints on ISL-violating Yukawa interactions with 1 μm $< \lambda <$ 1 cm. The heavy curves give experimental upper limits (the Lamoreaux constraint was computed in Reference (151)). Theoretical expectations for extra dimensions (56), moduli (101), dilaton (102), and radion (83) are shown as well.

DILATON RUN-AWAY SCENARIO

(Damour, Piazza, Veneziano)

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

DILATON COUPLING FUNCTIONS $B_i(\Phi)$



OBSERVATIONAL CONSEQUENCES TODAY

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

WEAK EQUIVALENCE PRINCIPLE VIOLATION

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

DIMENSIONLESS PARAMETERS (FROM INFLATION)

DENSITY FLUCTUATIONS : $\frac{\delta\rho}{\rho} \sim 5\times 10^{-5}$

VARIATION OF CONSTANTS

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

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

COUPLING TO DARK MATTER OR DARK ENERGY

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

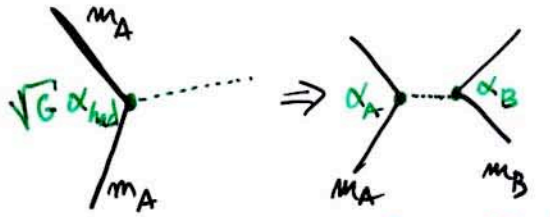
COUPLING TO ORDINARY MATTER

α_{had}

CORRELATED EFFECTS LINKED TO EQUIV.-PRINCIPLE VIOLATIONS

IF ∃ ULTRA-LIGHT "DILATON-LIKE", OR "MODULI-LIKE" FIELD φ

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



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

{ 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 $\frac{\partial}{\partial U}\ln\alpha, \dots$ } ARE ALL PROPORTIONAL TO α_{had}^2

EG:

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

$$\beta - 1 \simeq \frac{1}{2}\,\frac{\partial \alpha_{had}}{\partial \varphi}\,\alpha_{had}^2$$

$$\left(\frac{\Delta a}{a}\right)_{AB} \simeq 2\times10^{-5}\,\alpha_{had}^2\left[\Delta\left(\frac{E}{M}\right)_{AB} + c_B\,\Delta\left(\frac{B}{M}\right)_{AB} + c_D\,\Delta\left(\frac{D}{M}\right)_{AB}\right]$$

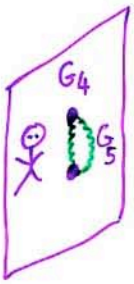
$E = \frac{Z(Z-1)}{(N+Z)^{1/3}}$, $B = N+Z$, $D = N-Z$

RESTRICTED DEPENDENCE ON A AND B

⇒ 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 $L \sim ct_0 \sim$ HUBBLE^{-1}, MIGHT EXPLAIN THE "ACCELERATION OF EXPANSION"
  - SMALL FRACTIONAL DEVIATIONS $\sim \frac{1}{L}\sqrt{\frac{r^3c^2}{GM}}$ FROM EINSTEIN ON ORDINARY SCALES

  ? BEST TESTABLE IN LUNAR RANGING ?

- TENSOR-SCALAR GRAVITY, $g_{\mu\nu} \oplus \varphi$, WITH BOTH $V(\varphi)$ AND $g^A_{\mu\nu} = B_A(\varphi)\, g_{\mu\nu}$ (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

FUTURE EXPERIMENTS ON GRAVITY

- GRAVITY PROBE B

ERES

- EXPLORING SUB-MICRON DEVIATIONS FROM NEWTON'S LAW

- OLD AND NEW BINARY PULSARS → MORE $\gamma-1 \sim 2.5\times10^{-6}$, $\beta-1 \sim 5\times10^{-6}$

- IMPROVED SOLAR-SYSTEM TESTS → GAIA (ESA, GLOBAL ASTROMETRY, 4-10 microarc) $\gamma-1 \sim 10^{-7}$; LATOR $\gamma-1 \sim 10^{-8}$

- GRAVITATIONAL WAVES
  - COALESCENCE OF BINARY BLACK HOLES
  - COALESCENCE OF BINARY NEUTRON STARS
  - GW BURSTS FROM CUSPS ON MASSIVE STRINGS

LIGO/VIRGO/GEO
LISA

- IMPROVED (SATELLITE) TESTS OF THE EQUIVALENCE PRINCIPLE
  - MICROSCOPE (2007), ONERA/CNES $\frac{\Delta a}{a} \sim 10^{-15}$
  - STEP, STANFORD/NASA/ESA/CNES $\frac{\Delta a}{a} \sim 10^{-18}$

- IMPROVED CMB MEASUREMENTS

PLANCK

MICROSCOPE (CNES) STEP (NASA/ESA/CNES) A26

SATELLITE TESTS OF THE EQUIVALENCE PRINCIPLE

ESA/NASA/CNES

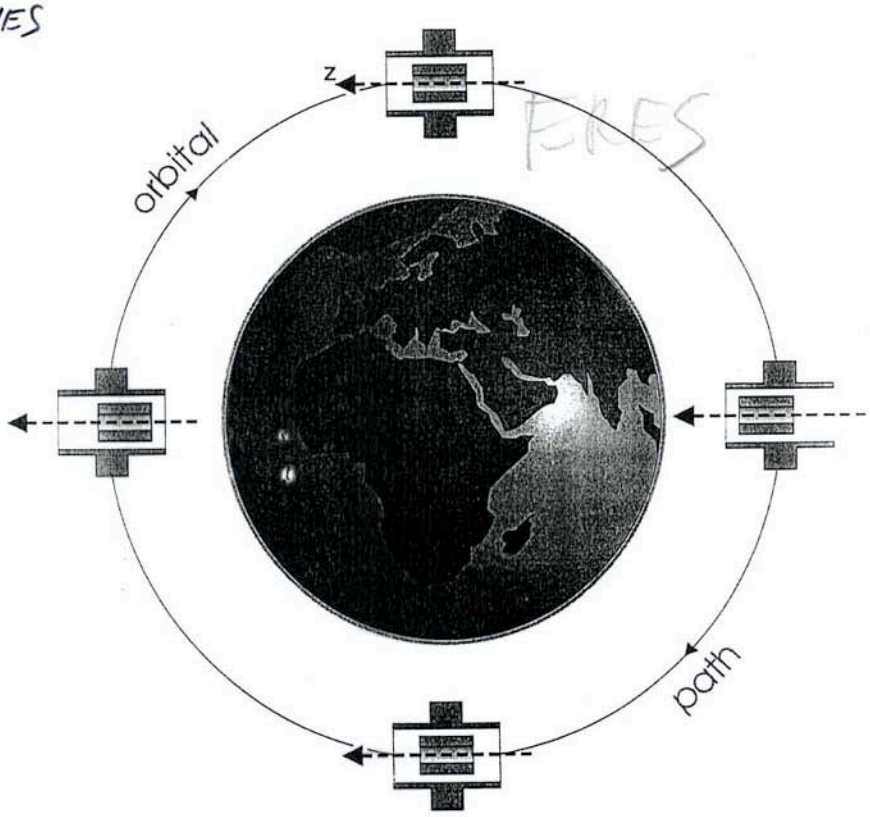
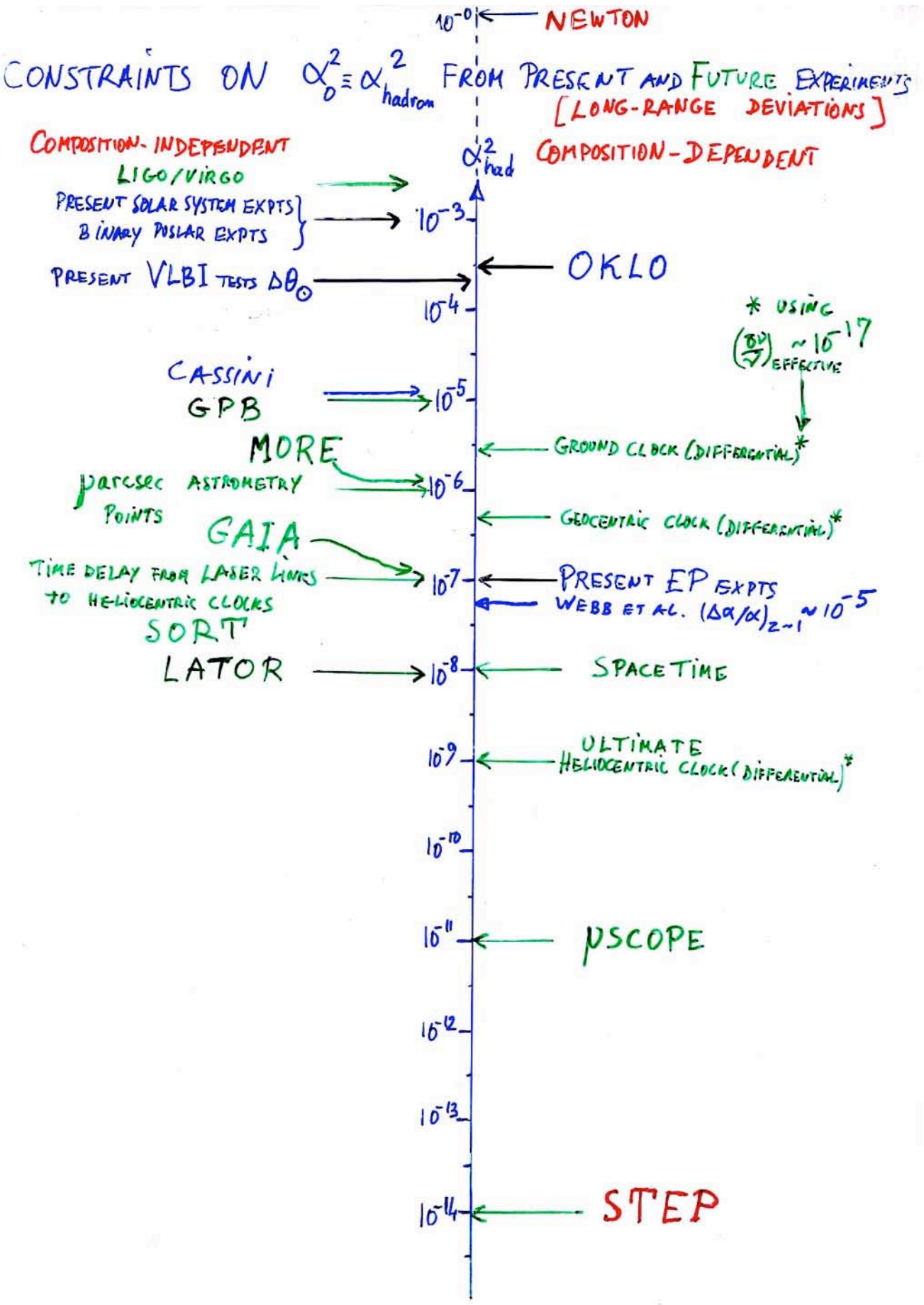


Fig. 3.2: *Equivalence principle violation: The Figure shows the relative motion of free masses where the ratio of inertial mass to gravititional mass depends on the composition of the masses. These test masses are constrained by linear magnetic bearings and sensing circuits. Here, the Equivalence Principle violation signal appears at the orbital frequency. In the normal mode of operation the spacecraft would be spun about an axis perpendicular to the orbital plane at a non-integral multiple of the orbital frequency, shifting the EP signal frequency to the spin-frequency ∓ the orbital frequency (depending on the spin sense).*


CONSTRAINTS ON $\alpha_0^2 \equiv \alpha^2_{hadron}$ FROM PRESENT AND FUTURE EXPERIMENTS
[LONG-RANGE DEVIATIONS]
COMPOSITION-INDEPENDENT
COMPOSITION-DEPENDENT
α^2_{had}
10^{-0}
NEWTON
LIGO/VIRGO
PRESENT SOLAR SYSTEM EXPTS
BINARY PULSAR EXPTS
10^{-3}
PRESENT VLBI TESTS $\Delta\theta_\odot$
OKLO
10^{-4}
* USING $\left(\frac{\delta\nu}{\nu}\right)_{EFFECTIVE} \sim 10^{-17}$
CASSINI
GPB
10^{-5}
MORE
GROUND CLOCK (DIFFERENTIAL)*
PARSEC ASTROMETRY POINTS
10^{-6}
GEOCENTRIC CLOCK (DIFFERENTIAL)*
GAIA
TIME DELAY FROM LASER LINKS TO HELIOCENTRIC CLOCKS
10^{-7}
PRESENT EP EXPTS
WEBB ET AL. $(\Delta\alpha/\alpha)_{z\sim1} \sim 10^{-5}$
SORT
LATOR
10^{-8}
SPACETIME
10^{-9}
ULTIMATE HELIOCENTRIC CLOCK (DIFFERENTIAL)*
10^{-10}
10^{-11}
μSCOPE
10^{-12}
10^{-13}
10^{-14}
STEP

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 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
  $a \simeq 9 \times 10^{-8}\ \mathrm{cm/s^2} \simeq c H_0$, BUT CANNOT BE UNIVERSAL (? $\not$EP)
  $\not\exists$ NO CONVINCING THEORETICAL MODEL

  ? + SOME CLAIMS OF VARIATION OF CONSTANTS (Webb ...; Petitjean ...)

- $\not\exists$ 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

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