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PHÉNOMÉNOLOGIE DE LA THÉORIE DES CORDES : SIGNAUX GRAVITATIONNELS POSSIBLES

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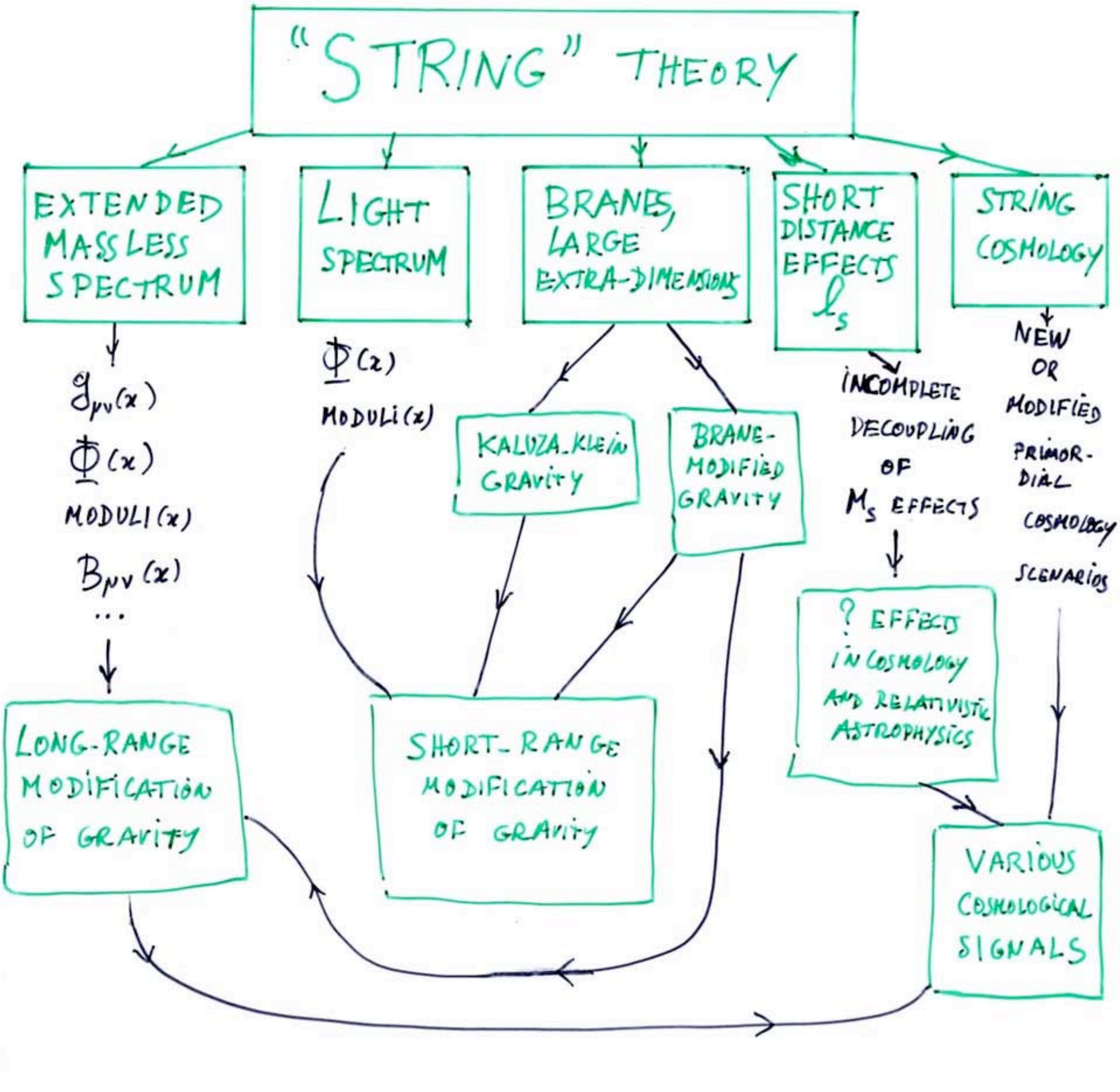
IHES

STRING-INSPIRED PHENOMENOLOGY

- 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 $(\ell_P, \dots, \ell_*, \dots)$ PHYSICS

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: $E^2 = m^2 + p^2 + \beta \ell_* E^3 + \dots$

BIREFRINGENCE OF VACUUM $\omega_\pm = |k| (1 \pm \beta \ell_* |k| + \cdots)$

VIOLATION OF LORENTZ INVARIANCE ?

DEFORMATION OF LORENTZ INVARIANCE

PARTICLE CREATION BY EXPANSION

QUANTUM DECOHERENCE: PURE STATES → MIXED STATES ?

VARIOUS OBSERVATIONAL WINDOWS

MODIFICATION OF CMB's C_ℓ (EXPANSION = MICROSCOPE!)

GREISEN-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 $\propto \ell_*^1 = \frac{1}{M_*^1}$ ∃ THEORETICAL DIFFICOLTIES
  ∃ SEVERE CONSTRAINTS FROM PRESENT DATA
- IF, MORE CONVENTIONALLY, $\propto \ell_*^2 = \frac{1}{M_*^2}$: TOO SMALL TO BE OBSERVED

+ OTHER POSSIBLE SIGNALS IN RELATIVISTIC ASTROPHYSICS

USUAL EXTREMAL LIMIT FOR BLACK HOLES:

$$\text{in } D=4 \quad GM^2 \leqslant \frac{J^2}{GM^2} + Q^2$$

Q^2: CAN BE LINKED TO BPS COND.

GM^2: NOT LINKED TO BPS; MODIFIED IN $D > 4$ (Myers....)

∃ ? "SUPERSPINARS" ? (Hořava, Gimon)

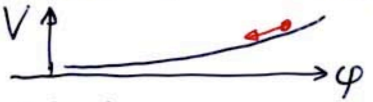
based on supertubes (Emparan, Mateos, Townsend...) ⇒ ? STABILITY ?

VARIOUS COSMOLOGICAL SCENARIOS

- STANDARD COSMOLOGICAL "SCENARIO" TO EXPLAIN WHY UNIVERSE SO LARGE, SO HOMOGENEOUS, + $\frac{\delta \rho}{\rho} \sim 5 \times 10^{-5}$

GR IS VALID

$\exists$ 'INFLATON' φ WITH $V(\varphi)$ VERY FLAT



$\epsilon \sim M_P^2 \left(\frac{V'}{V}\right)^2 \ll 1$ AND $\eta \sim M_P^2 \frac{V''}{V} \ll 1$

QUANTUM FLUCT. $\hat{\delta\varphi} \Rightarrow$ ADIABATIC GAUSSIAN $\frac{\delta \rho}{\rho}$

$\frac{\delta \rho}{\rho} \sim 5 \times 10^{-5} \Leftrightarrow \exists$ SMALL PARAMETER

$V(\varphi) = \lambda \varphi^4$ or $\frac{1}{2} m^2 \varphi^2$ $\quad \lambda \sim 10^{-13}$

$m^2 \sim 10^{-12} m_P^2$

- STRING THEORY CHALLENGES

- FIND A NATURAL CANDIDATE FOR THE INFLATON FIELD φ

E.G. DILATON (Veneziano, Gasperini ...)

SEPARATION OF D-BRANES (Dvali, Tye; Burgess...Quevedo; KKLT, KKLMMT, ...)

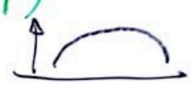
- GET GR WITHOUT DILATON-MODULI EFFECTS WHICH "KILL" INFLATION BY INTRODUCING "STEEP" DIRECTIONS IN $V(\varphi, \Phi, ...)$

E.G. WARPED FLUX COMPACTIFICATIONS (Giddings, Kachru, Polchinski; Kachru et al...

- ARRANGE EXISTENCE OF SLOW-ROLL REGIONS OF $V(\varphi)$

E.G. LARGE BRANE SEPARATION: (Dvali, Tye; ...; KKLMMT

OR SYMMETRIC CONFIGURATIONS (Trivedi, ...



OR HIGH-DERIVATIVE TERMS $\sim -f(\phi)\sqrt{1+f(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi} - V(\phi)$ (Silverstein, Tong)

à la k-inflation (Armendariz-Picon, Damour, Mukhanov; Garriga, Mukhanov)

- TUNE-IN SOME SMALL PARAMETER ($\lambda \sim 10^{-13}$) TO ARRANGE $\frac{\delta \rho}{\rho} \sim 5 \times 10^{-5}$
- INCORPORATE STANDARD MODEL, AND ARRANGE FOR REHEATING
- ? ARRANGE INITIAL CONDITIONS, OR USE "ANTHROPIC-LIKE" ARGUMENTS

VARIOUS COSMOLOGICAL SIGNALS

- TILT OF POWER SPECTRUM LARGE/SMALL POSITIVE/NEGATIVE

$$\frac{d n_s}{d \ln k}$$

- NON GAUSSIANITY E.G. DBI ⇒ LOWER BOUND ON NON-GAUSSIANITY (Alishahiha, Silverstein, Tong)

  OTHER MODELS ⇒ NEGLIGIBLE NON-GAUSSIANITY

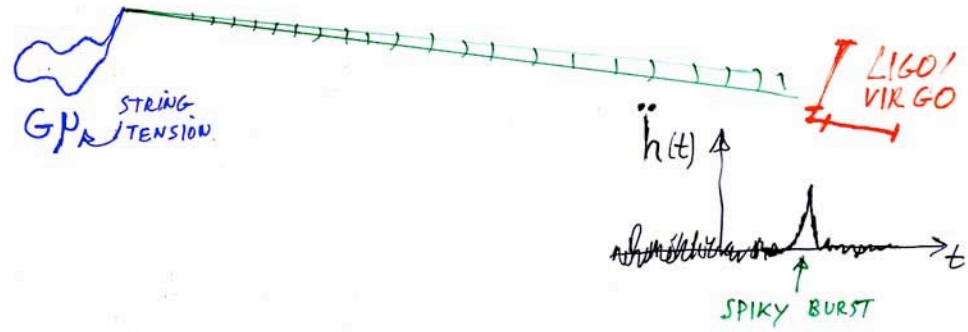
- TENSOR COMPONENT OF CMB SPECTRUM EG DBI ⇒ LARGE, OBSERVABLE TENSOR COMPONENT

- COSMIC SUPER-STRINGS (Copeland, Myers, Polchinski, Dvali, Vilenkin, ...
  FORMED FROM BRANE-$\overline{\text{BRANE}}$ ANNIHILATION (COMPLEX TACHYON)

  ↳ GRAVITATIONAL WAVE BURSTS (Damour, Vilenkin)

GRAVITATIONAL WAVE BURSTS FROM MASSIVE STRINGS

(Damour, Vilenkin '00)



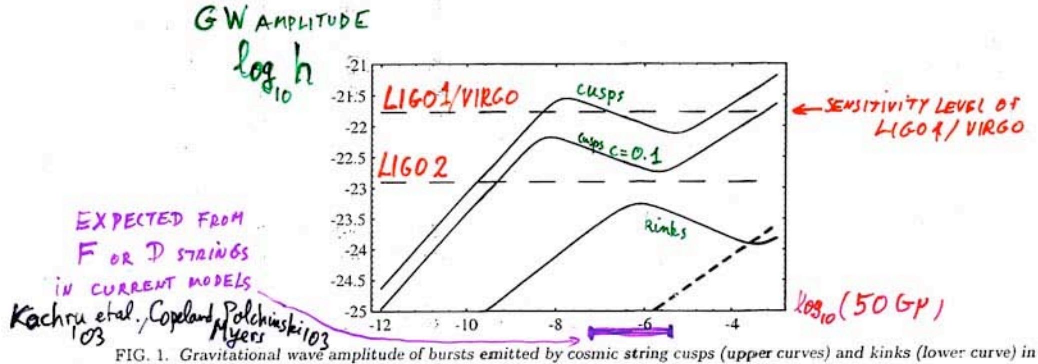


FIG. 1. *Gravitational wave amplitude of bursts emitted by cosmic string cusps (upper curves) and kinks (lower curve) in the LIGO/VIRGO frequency band, as a function of the parameter* $\alpha = 50\,G\mu$ *(in a base-10 log-log plot). The upper curve assumes that the average number of cusps per loop oscillation is* $c = 1$. *The middle curve assumes* $c = 0.1$. *The lower curve gives the kink signal (assuming only one kink per loop). The horizontal dashed lines indicate the one sigma noise levels (after optimal filtering) of LIGO 1 (initial detector) and LIGO 2 (advanced configuration). The short-dashed line indicates the "confusion" amplitude noise of the stochastic GW background.*

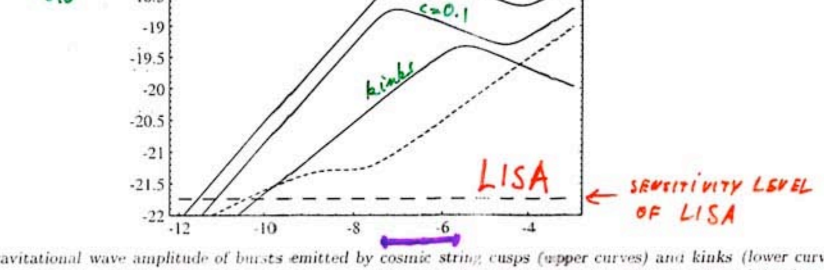


FIG. 2. *Gravitational wave amplitude of bursts emitted by cosmic string cusps (upper curves) and kinks (lower curve) in the LISA frequency band, as a function of the parameter* $\alpha = 50\,G\,\mu$ *(in a base-10 log-log plot). The meaning of the three solid curves is as in Fig. 1. The short-dashed slanted curve indicates the confusion noise. The lower long-dashed line indicates the one sigma noise level (after optimal filtering) of LISA.*

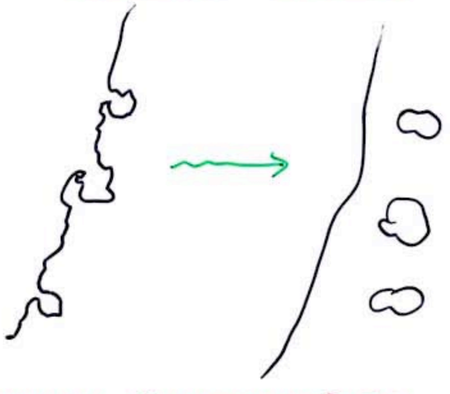
GRAVITATIONAL RADIATION FROM COSMIC SUPERSTRINGS

(Damour, Vilenkin '04)

STANDARD FIELD-THEORY STRINGS

- RECONNECTION PROBABILITY $\boxed{\overset{\text{STANDARD}}{p} \simeq 1}$

- STANDARD ESTIMATE OF SIZE OF WIGGLES AND NEWLY FORMED LOOPS (Bennett, Bouchet '88)



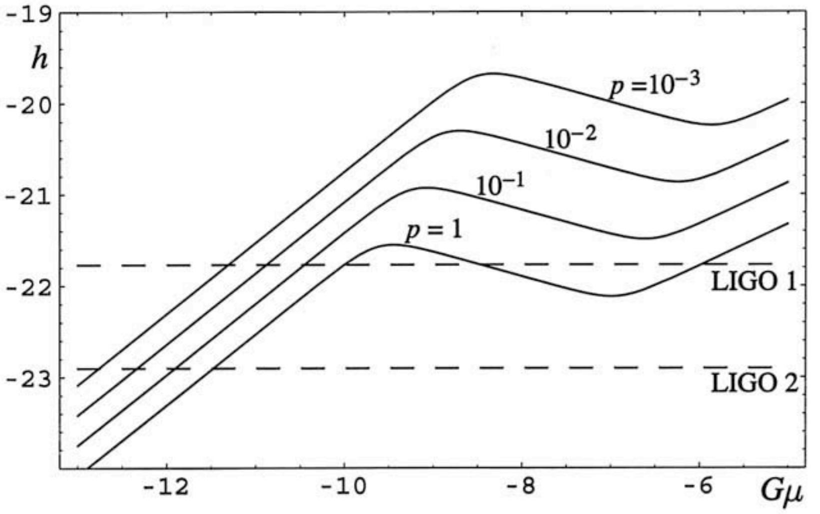
$$\boxed{\overset{\text{STANDARD}}{\ell} \sim 50 G\mu t}$$

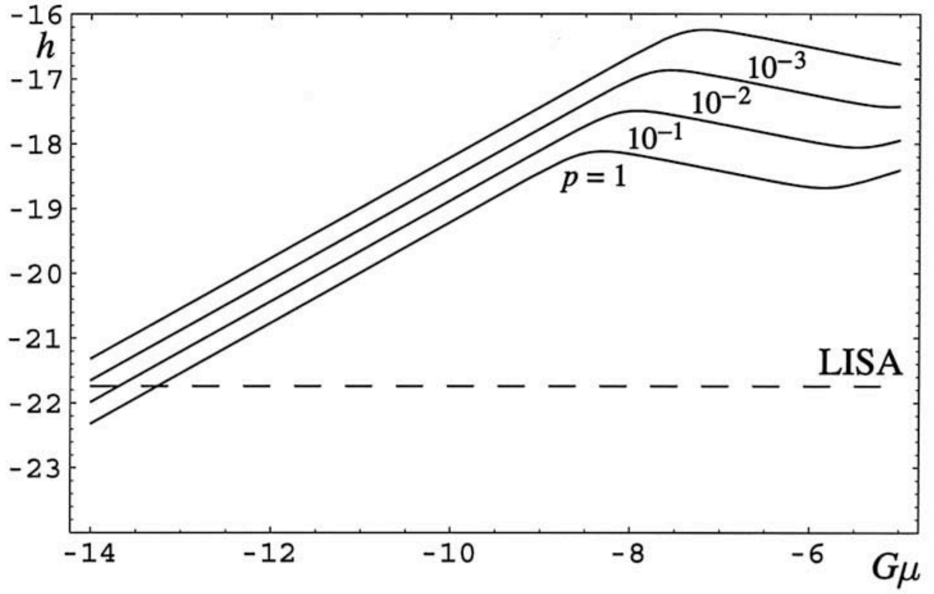
COSMIC SUPERSTRINGS

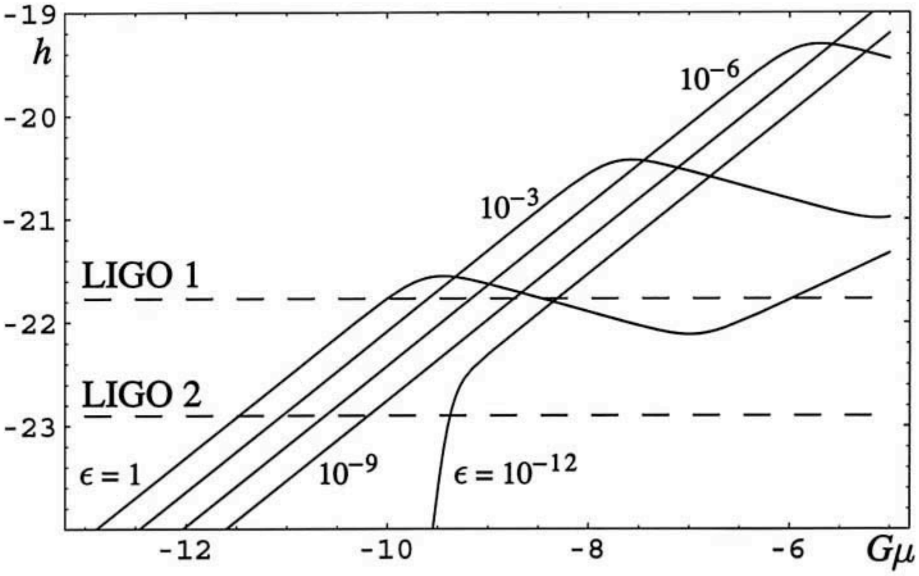
$$\boxed{10^{-3} \lesssim p \lesssim 1}$$

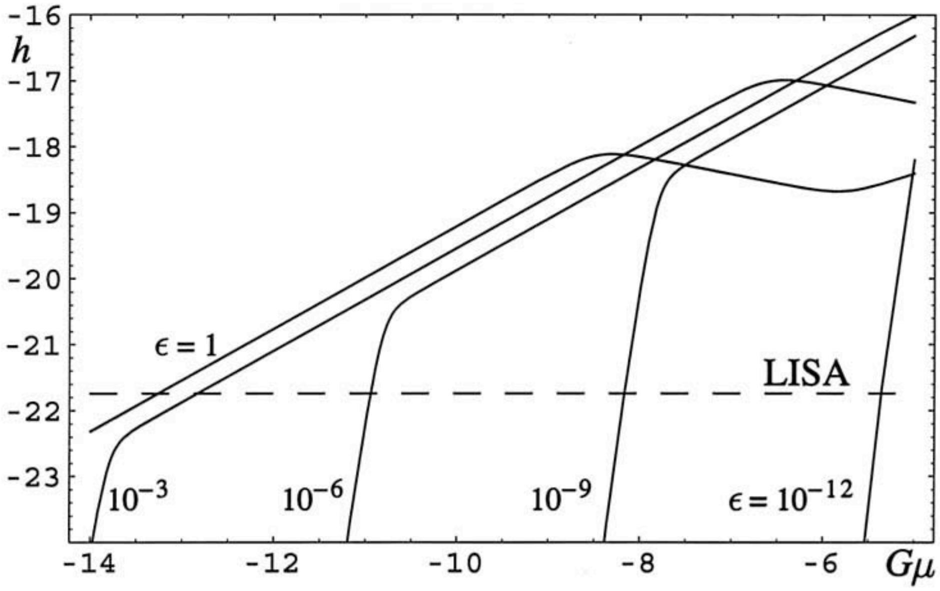
REVISED ESTIMATE OF EFFECT OF RADIATION REACTION ON SPECTRUM OF WIGGLES (Siemens, Olum, Vilenkin '02)

$$\boxed{\begin{array}{c} \ell \sim \epsilon\, 50 G\mu t \\ \epsilon \ll 1 \end{array}}$$

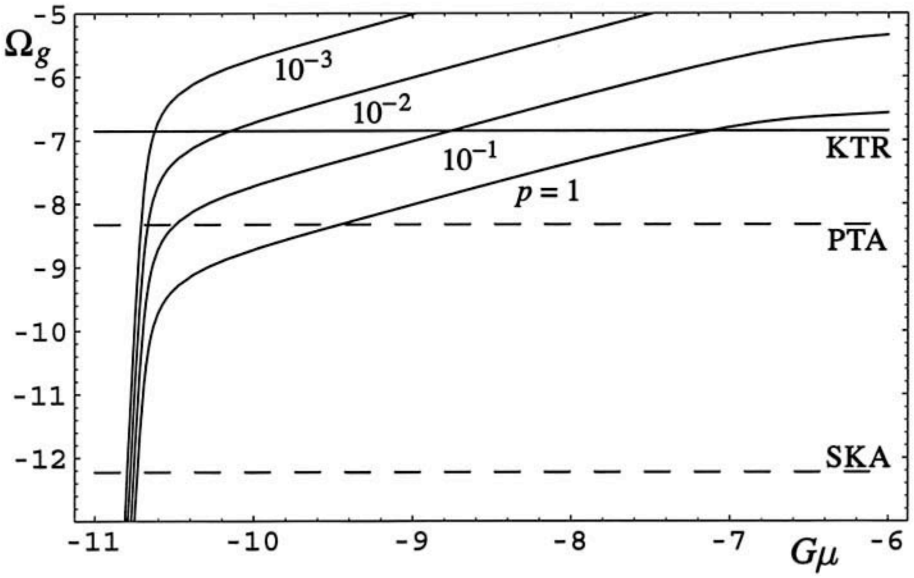

-19
h
-20
-21
-22
-23
-12
-10
-8
-6
Gμ
p =10^-3
10^-2
10^-1
p = 1
LIGO 1
LIGO 2

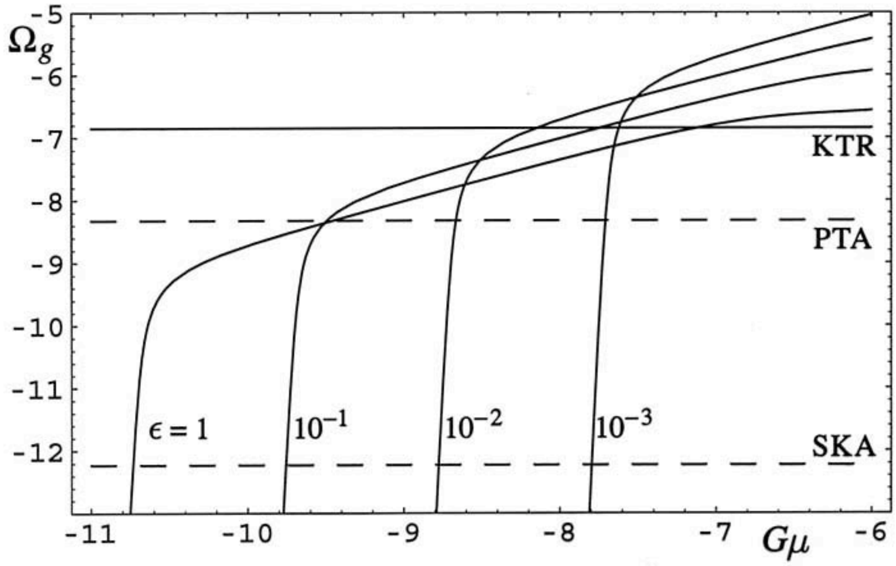

h
-16
-17
-18
-19
-20
-21
-22
-23
-14
-12
-10
-8
-6
$G\mu$
10^{-3}
10^{-2}
10^{-1}
$p = 1$
LISA


-19
h
-20
-21
-22
-23
LIGO 1
LIGO 2
10^{-6}
10^{-3}
$\epsilon = 1$
10^{-9}
$\epsilon = 10^{-12}$
-12
-10
-8
-6
$G\mu$



-16
h
-17
-18
-19
-20
-21
-22
-23
-14
-12
-10
-8
-6
$G\mu$
$\epsilon = 1$
LISA
10^{-3}
10^{-6}
10^{-9}
$\epsilon = 10^{-12}$


Ω_g
-5
-6
-7
-8
-9
-10
-11
-12
10^{-3}
10^{-2}
10^{-1}
$p = 1$
KTR
PTA
SKA
-11
-10
-9
-8
-7
-6
$G\mu$

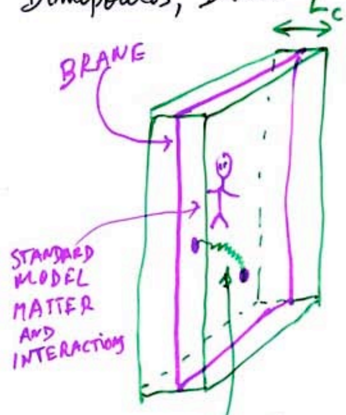


Ω_g
-5
-6
-7
-8
-9
-10
-11
-12
KTR
PTA
SKA
$\epsilon = 1$
10^{-1}
10^{-2}
10^{-3}
-11
-10
-9
-8
-7
$G\mu$
-6

BRANES AND GRAVITY

"LARGE" BUT COMPACT EXTRA-DIMENSIONS

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali



BULK GRAVITY

⇓

HIGHER-DIMENSIONAL GRAVITY WHEN

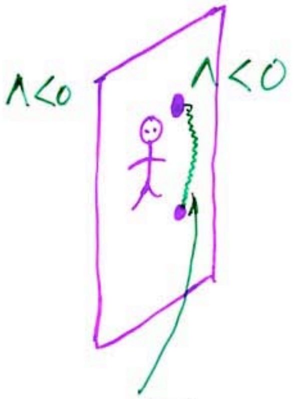
$r < L_c$

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

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

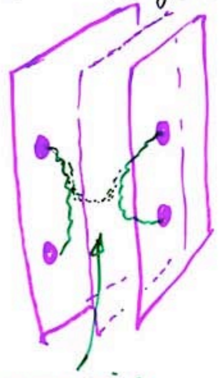
AND SMALL MODIFICATIONS FOR $r < L$

E.G. (Gruzinov)

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

MULTI-BRANES

Kogan, Mouslopoulos, Papazóglou, Ross, Santiago, Gregory, Rubakov, Sibiryakov



TUNNELLING (EVANESCENT WAVES) BETWEEN SEVERAL GRAVITON WAVES

⇓

MULTI-GRAVITY

⇓

MODIFICATION OF GRAVITY WHEN

$r \lesssim r_c$

AND

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

BUT PROBLEMS WITH "PAULI-FIERZ"-TYPE MASSIVE GRAVITY

INVERSE-SQUARE LAW TESTS

(Adelberger, Heckel, Nelson /03)

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

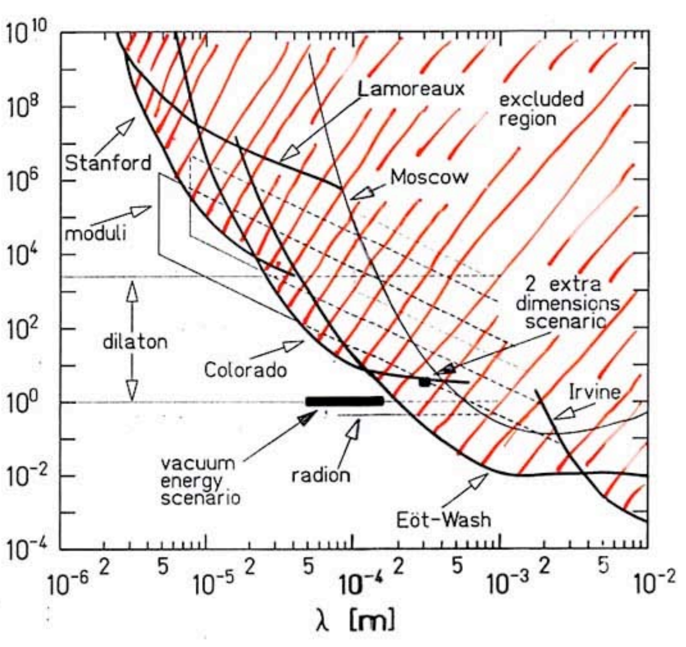


Figure 5: 95%-confidence-level constraints on ISL-violating Yukawa interactions with 1 μm $< \lambda <$ 1 cm. The heavy curves give experimental upper limits (the Lamoreaux constraint was computed in Reference (151)). Theoretical expectations for extra dimensions (56), moduli (101), dilaton (102), and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

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

	GEOMETRY	COUPLING CONSTANTS
NEWTON	RIGID	RIGID
EINSTEIN	SOFT	RIGID
STRING THEORY	SOFT	SOFT

EINSTEIN EQUIVALENCE PRINCIPLE

VIOLATION OF THE EQUIVALENCE PRINCIPLE

$$g \sim g \sim g \sim G$$

geometry, gravitation, gauge coupling constants, gravitational coupling constant

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

$$g_s(x) = e^{\Phi(x)} \qquad G(x) \propto g_s^2(x) = e^{2\Phi(x)} + \cdots$$

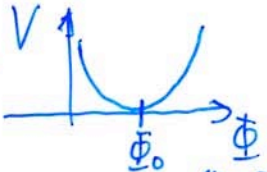
$$\mathcal{L}_{EFF} = e^{-2\Phi(x)}\left[R(g) + 4(\nabla\Phi)^2 - \frac{1}{12}H^2_{\mu\nu\lambda} - \frac{1}{4}F^2_{\mu\nu} - i\bar{\psi}D\psi - \cdots\right]$$

$$+ \mathcal{O}\left((\alpha'\partial^2)^n\right) + \mathcal{O}\left(e^{+n\Phi}\right)$$

(FRADKIN, TSEYTLIN '85), (CALLAN ET AL '85 ....)

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

① $V(\Phi) \simeq \frac{1}{2} m_\Phi^2 (\Phi - \Phi_0)^2$



IN LOW-ENERGY WORLD

$\Rightarrow$ ONLY SHORT-RANGE EFFECTS $\propto e^{-m_\Phi r}/r$

RECENT EXPERIMENTS
Hoyle ... 2001
Chiaverini ... 2003
Long --- 2003
Adelberger .. 2003

$\Rightarrow \quad \lambda_\Phi = \frac{1}{m_\Phi} \lesssim 0.1\,\text{mm} \Rightarrow m_\Phi \gtrsim 10^{-3}\,\text{eV}$

SOME MODELS NEED TO FIX Φ DURING INFLATION $\Rightarrow m_\Phi \gg H_{INF}$

POSSIBLY $V(\Phi) \sim M_{susy}^4 \, \tilde{V}\left(\frac{\Phi}{M_P}\right) \Rightarrow m_\Phi \sim \frac{M_{susy}^2}{M_P} \sim \frac{(1\,\text{TeV})^2}{2.4\times 10^{18}\,\text{GeV}} \sim \underline{10^{-3}\,\text{eV}}$ (Taylor Veneziano, Ferrara...., Antoniadis...

ACCESSIBLE TO "CAVENDISH" EXPTS

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

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

IF $\exists \, \Phi_m ; \; \partial B_i(\Phi_m)/\partial\Phi_m = 0$ (Damour, Nordtvedt; Damour Polyakov)

$\exists$ COSMOLOGICAL ATTRACTOR MECHANISM $\Phi \longrightarrow \Phi_m$
AND Φ NEARLY DECOUPLES FROM MATTER WHEN $\Phi \simeq \Phi_m$
$\Rightarrow$ NATURALLY SUPPRESSED MODIFICATIONS OF LONG-RANGE GRAVITY

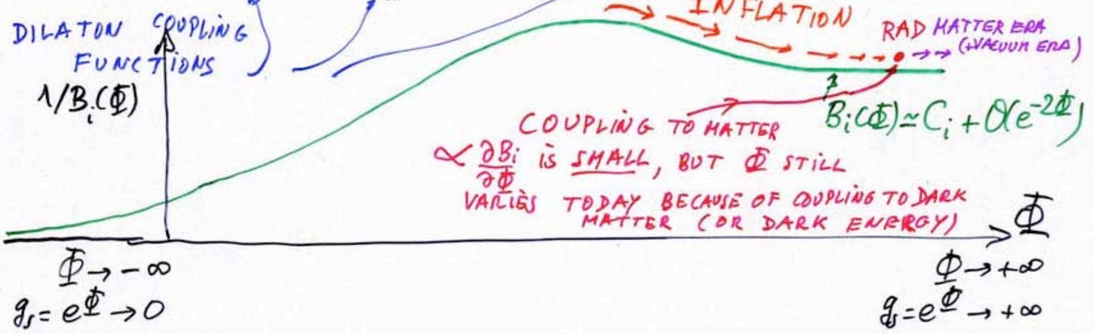
③ BOTH A QUINTESSENCE-LIKE $V(\Phi) \neq 0$ AND COUPLING TO MATT. $B_i(\Phi)$
$\Rightarrow m_\Phi$ DEPENDS ON SURROUNDING MATTER DENSITY, SO THAT
Φ IS SHORT-RANGED IN EARTH-BOUND EXPERIMENTS
(Khoury, Weltman; Brax....)

DILATON RUN-AWAY SCENARIO

(Gasperini, Piazza, Veneziano '01, Damour, Piazza, Veneziano '02)

JORDAN-FIERZ-TYPE COUPLING

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



OBSERVATIONAL CONSEQUENCES TODAY

EQUIVALENCE PRINCIPLE VIOLATION

DENSITY FLUCTUATIONS $\delta\rho/\rho \sim 5\times10^{-5}$

$$\boxed{\frac{\Delta a}{a} \sim 5\times10^{-4}\left(\frac{b_F}{b_\lambda c}\right)^2 \left(\frac{\delta\rho}{\rho}\right)^{\frac{8}{n+2}} \sim (b_F/b_\lambda c)^2 \times 10^{-12}}$$

INFLATIONARY POTENTIAL

$V(\chi) = \lambda(\Phi)\,\chi^n$

IF $n=2$ (WMAP favored)

VARIATION OF CONSTANTS

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

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

COUPLING TO COSMOLOGICAL ENERGY DENSITY : 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}

CONCLUSIONS

'BEYOND GENERAL RELATIVITY': 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

- 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, HALOES OF GALAXIES 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 $(\overset{?}{\cancel{EP}})$

    $\nexists$ NO CONVINCING THEORETICAL MODEL
  - ? ~ SOME CLAIMS OF VARIATION OF CONSTANTS (Webb...

    Petitjean et al..04

    $$\frac{\Delta(m_p/m_e)}{m_p/m_e} = (2.97 \pm 0.74) \times 10^{-5} \text{ over } 12\text{ Gyrs}$$

- IMPORTANT TO IMPROVE TESTS OF GR, AND TO LOOK FOR DEVIATIONS

RECAP OF SOME POSSIBLE LONG-RANGE MODIFICATIONS OF GRAVITY

- BRANE-INDUCED + BULK GRAVITY (Dvali, Gabadadze, Porrati)
  - NO VIOLATION OF EQUIVALENCE PRINCIPLE
  - $\exists$ LENGTH SCALE $L \equiv G_5 / G_4$
    IF $L \sim ct_0 \sim H_0^{-1}$ MIGHT EXPLAIN "ACCELERATED EXPANSION"
  - ON $r \ll L$, $\exists$ SMALL FRACTIONAL DEVIATIONS $\sim \frac{1}{L}\sqrt{\frac{r^3c^2}{GM}}$ FROM GR.
    BEST TESTABLE IN LUNAR RANGING? (Dvali, Zaldarriaga)
- RUN-AWAY DILATON $g_{\mu\nu}$ + WEAKLY-COUPLED MASSLESS φ
  - VIOLATIONS OF EQUIVALENCE PRINCIPLE: $\frac{\Delta a}{a} \lesssim 10^{-12}$
  - CORRELATED EFFECTS EG $\frac{\Delta a}{a} \sim 10^{-12}$; $\gamma - 1 \sim 10^{-7}$, $\frac{\dot{\alpha}_{EM}}{\alpha_{EM}} \sim 10^{-16}\,yr^{-1}$
  - PREDICTIONS FOR COMPOSITION DEPENDENCE $\left(\frac{\Delta a}{a}\right)_{AB} \simeq 10^{-5}(1-\gamma)\left[\Delta\overset{Z(Z-1)/(N+Z)^{1/3}}{\left(\frac{E}{M}\right)}_{AB} + c_B\,\Delta\left(\frac{B}{M}\right)_{AB} + c_D\,\Delta\left(\frac{D}{M}\right)_{AB}\right]$
- $g_{\mu\nu} + \varphi$ WITH **BOTH** $V(\varphi)$ AND $g^{A}_{\mu\nu} = B_A(\varphi)\, g_{\mu\nu}$ (Khoury, Weltman)
  - CAN INCORPORATE EP VIOLATIONS
  - m_φ DEPENDS ON SURROUNDING $\rho \Rightarrow$ "CHAMELEON EFFECT"
  - POSSIBLE SIGNIFICANT MODIFICATIONS OF GRAVTY IN SPACE VS EART-BOUND EXPTS
- E.G. $g_{\mu\nu}$ + MASSIVE $B_{[\mu\nu]}$ (EINSTEIN; Damour, Deser, McCartly; Moffat)
  - NECESSARILY INCORPORATES EP VIOLATION
  - CONTAINS MASSIVE VECTOR INTERACTIONS
  - POSSIBLE STRONG-FIELD DEVIATIONS

COMPARISON OF POTENTIAL MEASUREMENTS OF α_{QCD}^2

USUAL
PPN PARAMETERS

$$\gamma_{Edd} - 1 = -2\,\frac{\alpha_{QCD}^2}{1+\alpha_{QCD}^2}$$

$$\beta_{Edd} - 1 = \frac{1}{2}\,\frac{\beta_{QCD}\,\alpha_{QCD}^2}{(1+\alpha_{QCD}^2)^2}$$

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