STONY BROOK
20-21 OCT 05

GENERAL RELATIVITY, EXPERIMENT AND GRAVITATIONAL WAVES

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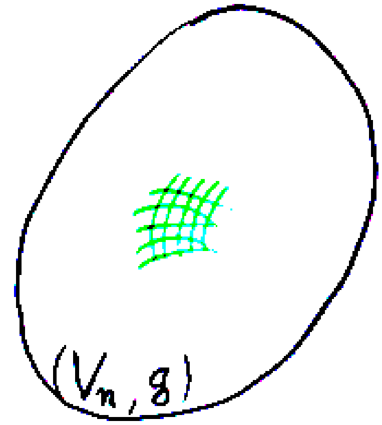
EINSTEIN'S VISION

BERN 1907

$$\vec{x}' = \vec{x} - \tfrac{1}{2}\vec{g}\,t^2$$

RIEMANN ~ 1856



LOCAL EFFACEMENT OF $\vec{g}$

$$\exists\, x'^{\mu};\ g'_{\mu\nu}(x'^{\lambda}) = f_{\mu\nu} + O[(x'-x'_0)^2]$$

LOCAL EFFACEMENT OF $\Gamma^{\lambda}_{\mu\nu} \sim \partial \underline{\underline{g}}$

UNIVERSALITY OF FREE FALL $\dashrightarrow$ $\leftarrow$ UNIVERSAL COUPLING OF MATTER TO ONE $g_{\mu\nu}(x^{\lambda})$

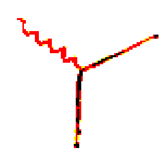
('HYPOTHESIS OF EQUIVALENCE')

['EQUIVALENCE PRINCIPLE']

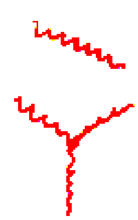
$$\boxed{S_{TOT} \simeq \frac{c^4}{16\pi G}\int \sqrt{g}\,\frac{d^4x}{c}\,R(g) + S_{MATTER}[\psi, A, H;\ g_{\mu\nu}]}$$

TWO SORTS OF EXPERIMENTAL TESTS

- MATTER-COUPLING TESTS (RHS)



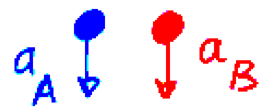
- TESTS OF THE DYNAMICS OF $g_{\mu\nu}$ (LHS)



TESTS OF THE COUPLING MATTER ∩ GRAVITY

"EQUIVALENCE PRINCIPLE" $S_{MATTER}[\psi, A, H; g_{\mu\nu}]$

- UNIVERSALITY OF FREE FALL



Adelberger's group $\left(\frac{\Delta a}{a}\right)_{Fe-Si} = (3.6 \pm 5.0_{STAT} \pm 0.7_{SYST}) \times 10^{-13}$

Lunar Laser Ranging's group $\left(\frac{\Delta a}{a}\right)_{\oplus ☽} = (-1.0 \pm 1.4) \times 10^{-13}$

- CONSTANCY OF "CONSTANTS" $\alpha_{EM} \equiv \frac{e^2}{\hbar c}$

Atomic Clock Tests
Marion...'03; Bize...'03; Fischer '05

$$\frac{\dot{\alpha}_{EM}}{\alpha_{EM}} = (-0.9 \pm 2.9) \times 10^{-15}\, yr^{-1}$$

Oklo's natural fission reactor
Shlyakhter '76, Damour Dyson '96, Fujii...'00

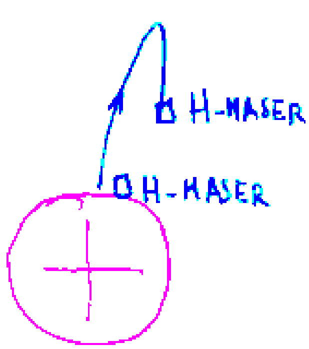
$$\frac{\langle \dot{\alpha}_{EM} \rangle}{\alpha_{EM}} = (-0.9 \pm 5.9) \times 10^{-17}\, yr^{-1}$$

Quasar absorption lines
Quast '04; Srianand...'04

$$\frac{\langle \dot{\alpha}_{EM} \rangle}{\alpha_{EM}} = (-0.7 \pm 1.9) \times 10^{-16}\, yr^{-1}$$

- GRAVITATIONAL REDSHIFT

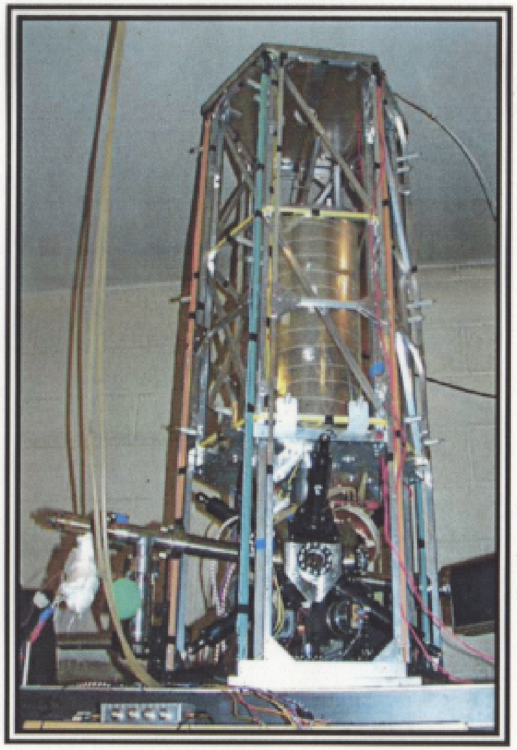
Vessot, Levine '79



$$\frac{\Delta\nu}{\nu} = (1 \pm 10^{-4}) \frac{\Delta U}{c^2}$$

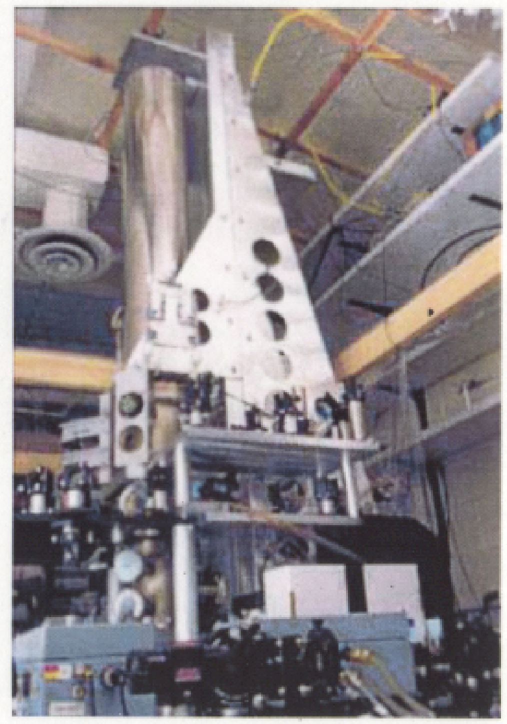
Fontaines Atomiques

8 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN. 5 with accuracy at 1 10^{-15} . More than 10 under construction.



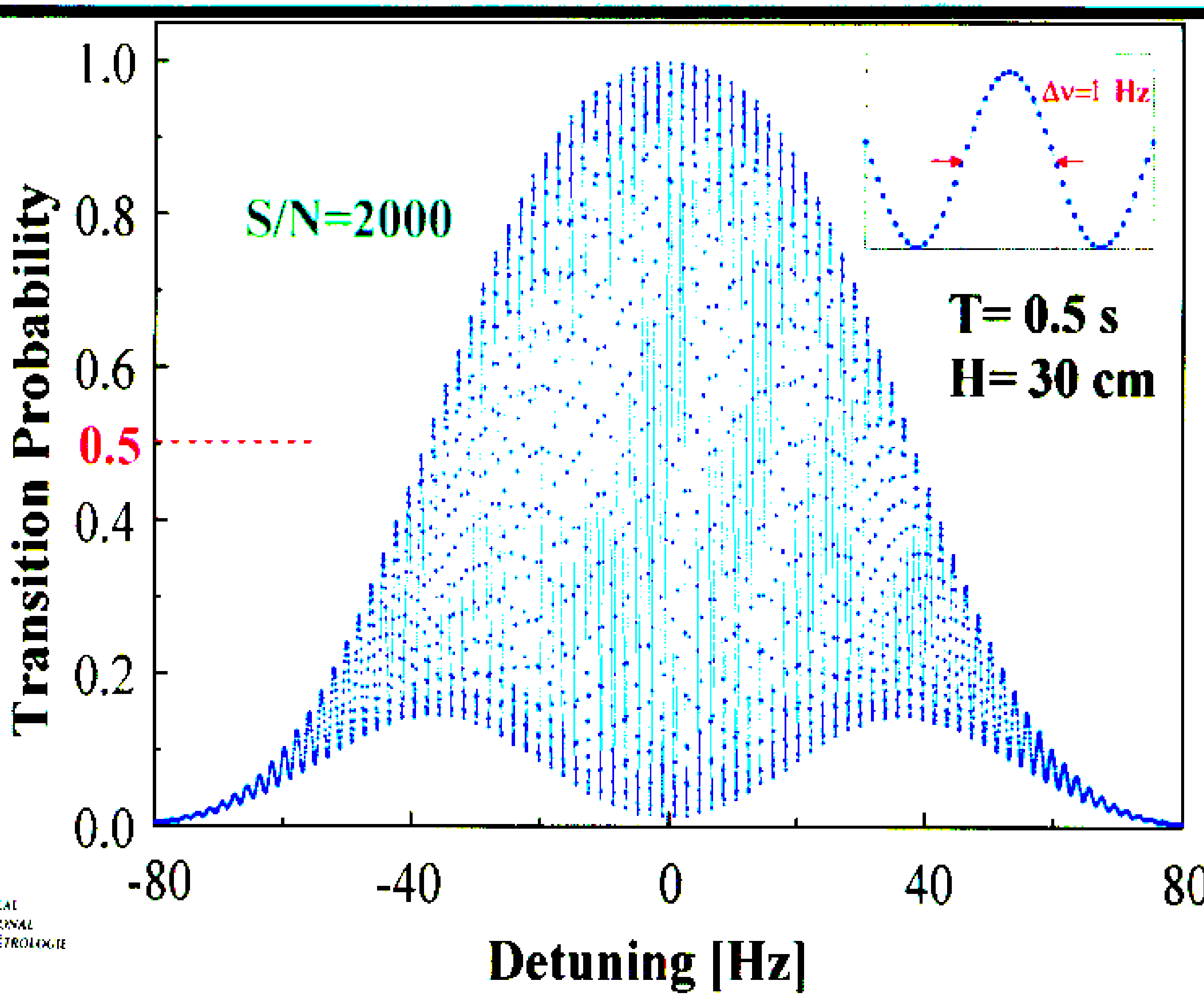
BNM-SYRTE, FR

PTB, D



NIST, USA

Franges de Ramsey dans une fontaine atomique



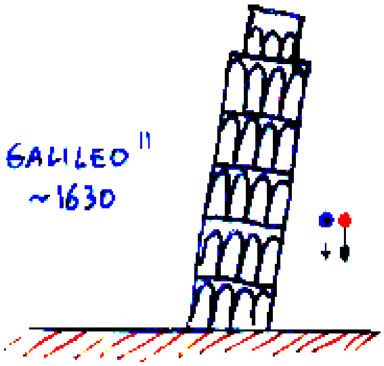
BNM BUREAU NATIONAL DE MÉTROLOGIE

SYRTE

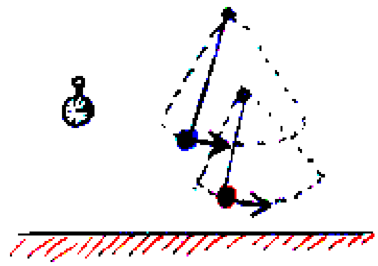
G. Santarelli et al., PRL 82, 4619 (1999)

UNIVERSALITY OF FREE FALL

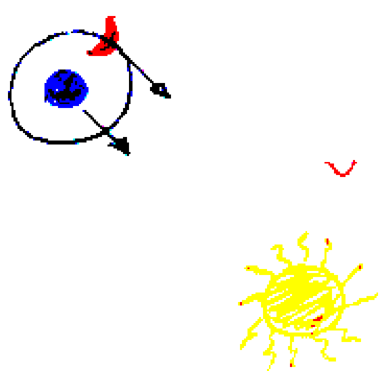
"GALILEO"
~1630



NEWTON
≤1686



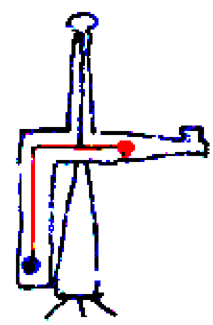
10^{-3}



$\sim 10^{-7}$

LAPLACE
≤1805

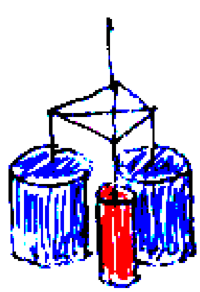
[POINCARÉ 1906 $\sim 10^{-8}$]



$\sim 10^{-8}$

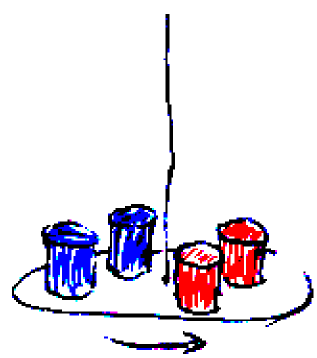
EÖTVÖS
1896

DICKE ET AL.
1962



$\sim 3\times 10^{-11}$

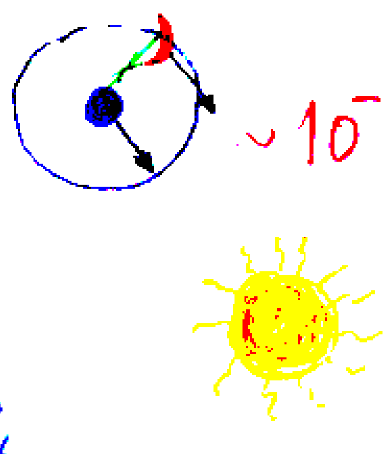
BRAGINSKY AND PANOV 1972



$\sim 10^{-12}$

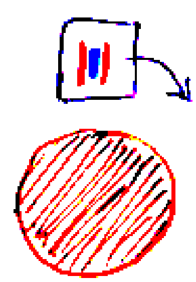
ADELBERGER ET AL.
1989-1994, 2001-

LUNAR
LASER
RANGING



$\sim 10^{-13}$

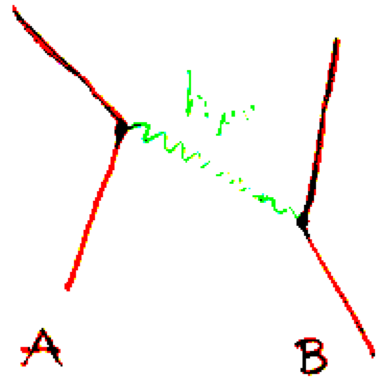
1969 – NOW
DICKEY ET AL. '94
WILLIAMS ET AL. '96



SPACE
TESTS
OF THE
EQUIVALENCE PRINCIPLE

MICROSCOPE 2009 $\sim 10^{-15}$?
STEP 200? $\sim 10^{-18}$?

DYNAMICS OF THE GRAVITATIONAL FIELD: WEAK FIELD REGIME



'ONE - GRAVITON EXCHANGE'

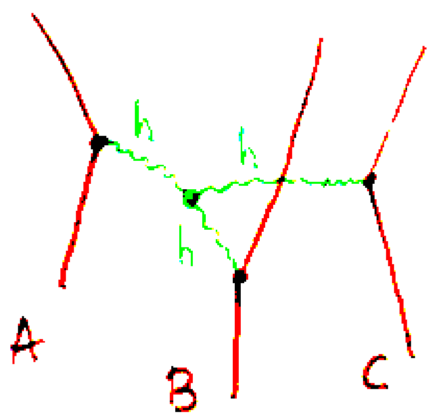
$\Updownarrow$

LINEARIZED EINSTEIN'S EQUATIONS

$$\Box h_{\mu\nu} = -\frac{16\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2} T \eta_{\mu\nu}\right)$$

$$S_{INT} = 2G \iint ds_A \, ds_B \; m_A u_A^{\mu} u_A^{\nu} \; P_{2\,\mu\nu}{}^{\rho\sigma} \, D[z_A(s_A) - z_B(s_B)] \; m_B u_{B\rho} u_{B\sigma}$$

$$L^{2\text{-body}} = \frac{1}{2}\sum_{A\neq B} \frac{G m_A m_B}{r_{AB}}\left[1 + \frac{3}{2c^2}(\vec{v}_A^{\,2} + \vec{v}_B^{\,2}) - \frac{7}{2c^2}\vec{v}_A\cdot\vec{v}_B - \frac{1}{2c^2}(\vec{n}_{AB}\cdot\vec{v}_A)(\vec{n}_{AB}\cdot\vec{v}_B) + O\left(\frac{1}{c^4}\right)\right]$$



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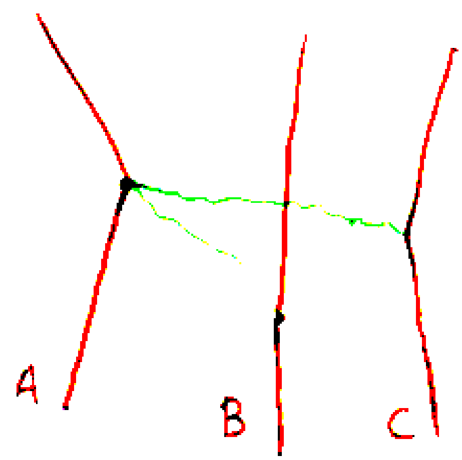


$$L^{3\text{-body}} = -\frac{1}{2}\sum_{B\neq A\neq C} \frac{G^2 m_A m_B m_C}{r_{AB}\, r_{AC}\, c^2} + O\left(\frac{1}{c^4}\right)$$

TESTS OF THE DYNAMICS OF THE GRAV. FIELD

SOLAR-SYSTEM TESTS :

WEAK ($h_{\mu\nu} < 10^{-6}$) AND QUASI-STATIC ($\frac{\partial_t h}{c\,\partial_x h} \sim \frac{v}{c} \lesssim 10^{-4}$) FIELDS

- PERIHELION ADVANCE OF MERCURY
  I. Shapiro '90, ASSUMING $J_2 \simeq 2\times 10^{-7}$

$$\Delta\dot{\varpi} = \underset{\dot{\varpi}^{GR}}{42''.98}\,(1.000 \pm 0.001)$$

- LIGHT DEFLECTION (VLBI)
  S. S. Shapiro... '04

$$\Delta\theta = \Delta\theta^{GR}\left(1 + (-0.9 \pm 2.2)\times 10^{-4}\right)$$

- ORBITAL MOTION OF THE MOON
  (Nordtvedt '68) LUNAR LASER RANGING
  Williams... '04

$$(\Delta r_{\oplus D})_{SYNODIC} = (3 \pm 4)\ \mathrm{mm}\ \cos D$$

- VARYING FREQUENCY SHIFT OF RADIO LINKS : CASSINI SPACECRAFT
  (Bertotti, Iess, Tortora '03)

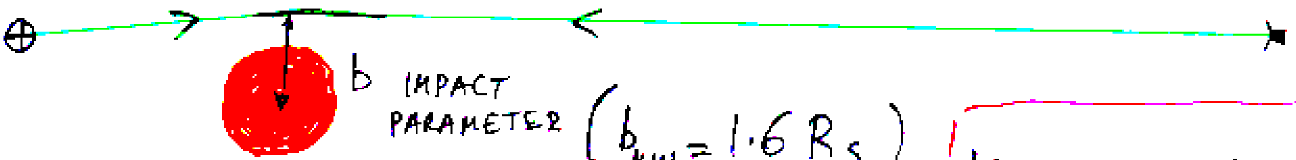
$$\frac{\Delta\nu/\nu}{(\Delta\nu/\nu)^{GR}} = 1 + (1.0 \pm 1.1)\times 10^{-5}$$

QUASI-STATIC, WEAK-FIELD EINSTEIN GRAVITY OK AT

10^{-5} LEVEL

VARYING FREQUENCY SHIFT OF RADIO LINKS WITH THE CASSINI SPACECRAFT

(Bertotti, Iess, Tortora '03)



$\left(b_{MIN} = 1.6\, R_S\right)$

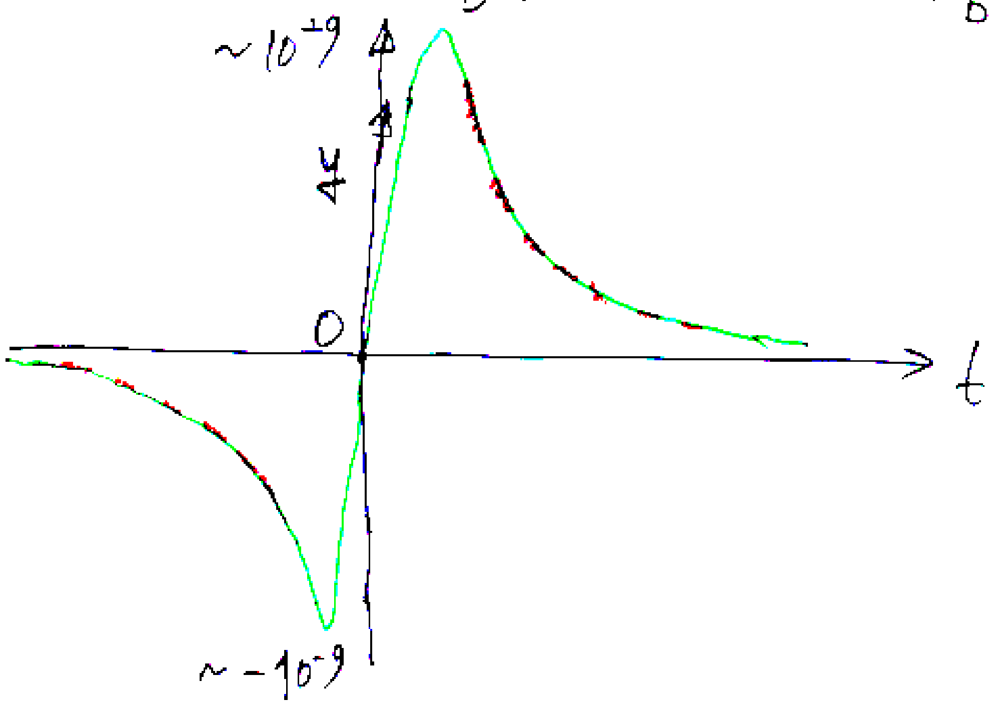
$$ds^2 = -\left(1 - 2\frac{U}{c^2} + 2\beta\frac{U^2}{c^4}\right)dt^2 + \left(1 + 2\gamma\frac{U}{c^2}\right)d\vec{x}^{\,2}$$

$\gamma_{GR} = 1$

TWO-WAY RELATIVISTIC FREQUENCY SHIFT

$$y = \left(\frac{\Delta\nu}{\nu}\right)^{\text{TWO-WAY}}_{\text{GRAV.}} = -4(1+\gamma)\frac{GM_{SUN}}{c^3 b}\frac{db}{dt} = -\,0.2\,\mu\text{sec}\,(1+\gamma)\frac{1}{b}\frac{db}{dt}$$

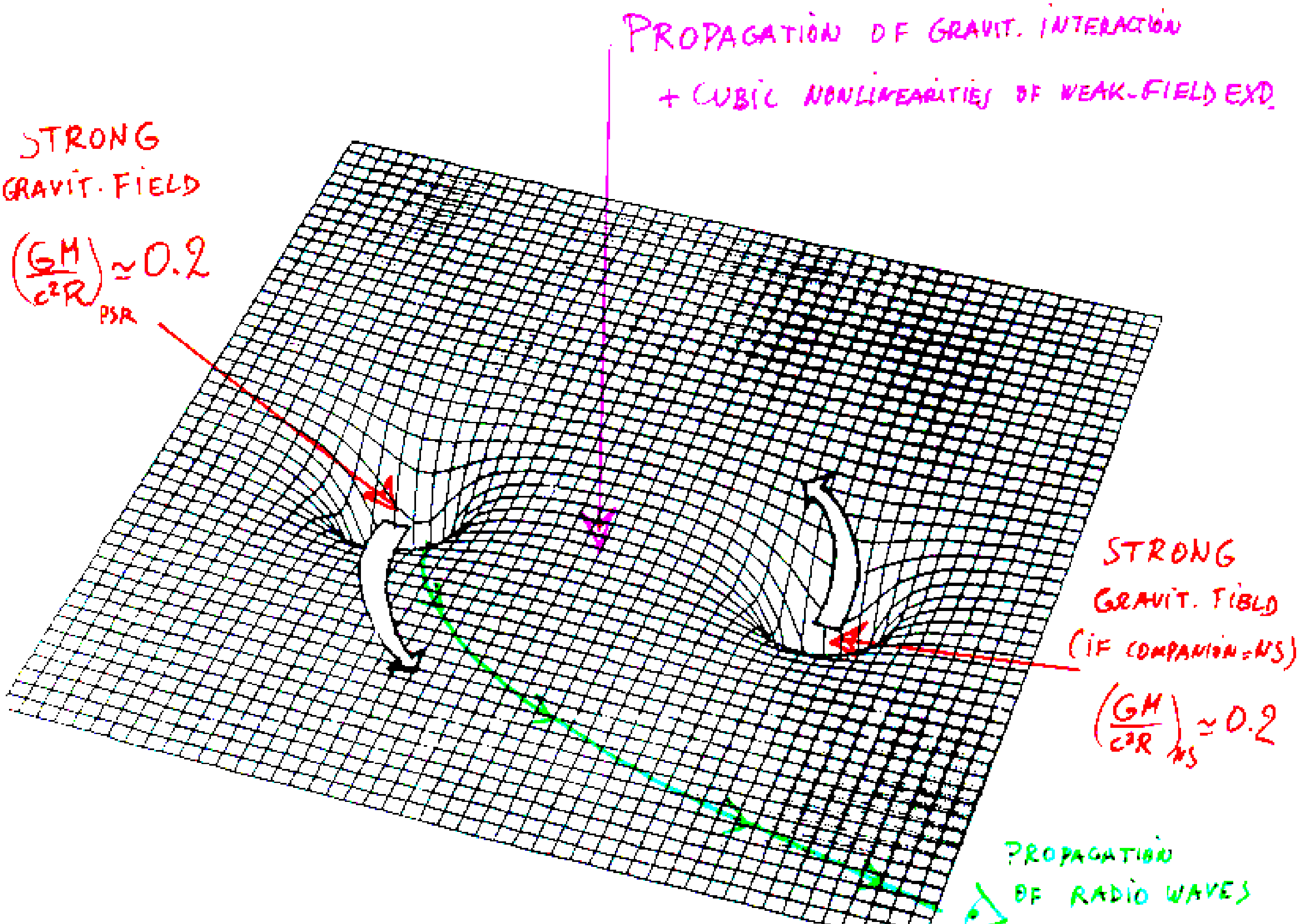
AS EARTH MOVES



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

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)

TESTING RELATIVISTIC GRAVITY WITH BINARY PULSAR DATA

TWO APPROACHES

- "THEORY-INDEPENDENT" OR "PHENOMENOLOGICAL"

  PARAMETRIZED POST-KEPLERIAN

- "THEORY-DEPENDENT"

  - BEYOND USUAL POST-NEWTONIAN PARAMETERS
  - CLASSES OF TENSOR-SCALAR THEORIES

USING BINARY PULSAR MEASUREMENTS TO PROBE RELATIVISTIC GRAVITY

TWO COMPLEMENTARY APPROACHES

1. PHENOMENOLOGICAL ANALYSIS OF BINARY PULSAR DATA

"PARAMETRIZED POST-KEPLERIAN FORMALISM" (PPK)

(Blandford + Teukolsky '76, D + Deruelle '86, D. '88, D + Taylor '92)

RAW PULSAR DATA $\{ t_N^{OBS} \}$

$\{ t_N^{THEOR} = F[N, P_i] \}$ — $i = 1, \cdots, 19$ PARAMETERS

GENERIC RELATIVISTIC TIMING FORMULA (D + Deruelle '86)

FIT

$$P_i^{OBS} \left(= P_i^{BEST\ FIT} \right) = \cdots \pm \cdots$$

EACH RELATIVISTIC THEORY OF GRAVITY PREDICTS

$$P_i^{THEOR} = f_i^{THEORY} \left(m_1, m_2 \ (, \lambda, \eta) \right)$$

REDUNDANCY : $19 - 2\ (-2) = 15$ TESTS OF RELATIVISTIC GRAVITY

MOST PROBE STRONG-FIELD ASPECTS OF GRAVITY

N.B. EACH SUCH TEST IS A POTENTIAL KILLER OF G.R.

RELATIVISTIC TIMING FORMULA

Damour and Deruelle [36, 47] proved that it is possible to describe all of the independent $O(v^2/c^2)$ timing effects in a simple mathematical way common to a wide class of alternative theories. This made it possible to revert to a theory-independent analysis of timing data, and led to the possibility of working within a strong-field analog of the PPN formalism, the so-called [37] "parametrized post-Keplerian" approach. The part of the Damour–Deruelle phenomenological timing model describing orbital effects reads

$$\boxed{t_b - t_0 = F[T; \{p^{\mathrm{K}}\}; \{p^{\mathrm{PK}}\}; \{q^{\mathrm{PK}}\}]\ ,} \tag{2.1a}$$

where t_b denotes the solar-system barycentric (infinite frequency) arrival time, T the pulsar proper time (corrected for aberration, see below),

$$\{p^{\mathrm{K}}\} = \{P_b, T_0, e_0, \omega_0, x_0\} \tag{2.1b}$$

is the set of Keplerian parameters,

$$\boxed{\{p^{\mathrm{PK}}\} = \{k, \gamma, \dot{P}_b, r, s, \delta_\theta, \dot{e}, \dot{x}\}} \tag{2.1c}$$

the set of *separately measurable* post-Keplerian parameters, and

$$\{q^{\mathrm{PK}}\} = \{\delta_r, A, B, D\} \tag{2.1d}$$

the set of *not separately measurable* post-Keplerian parameters. The right hand side of Eq. (2.1a) is given by

$$F(T) = D^{-1}[T + \Delta_R(T) + \Delta_E(T) + \Delta_S(T) + \Delta_A(T)]\ , \tag{2.2a}$$

$$\Delta_R = x \sin\omega[\cos u - e(1+\delta_r)] + x[1 - e^2(1+\delta_\theta)^2]^{1/2} \cos\omega \sin u\ , \tag{2.2b}$$

$$\Delta_E = \gamma \sin u\ , \tag{2.2c}$$

$$\Delta_S = -2r\ \ln\{1 - e\cos u - s[\sin\omega(\cos u - e) + (1-e^2)^{1/2}\cos\omega \sin u]\}\ , \tag{2.2d}$$

$$\Delta_A = A\{\sin[\omega + A_e(u)] + e\sin\omega\} + B\{\cos[\omega + A_e(u)] + e\cos\omega\}\ , \tag{2.2e}$$

where

$$x = x_0 + \dot{x}(T - T_0)\ , \tag{2.3a}$$

$$e = e_0 + \dot{e}(T - T_0)\ , \tag{2.3b}$$

and where $A_e(u)$ and ω are the following functions of u,

$$A_e(u) = 2\arctan\left[\left(\frac{1+e}{1-e}\right)^{1/2} \tan\frac{u}{2}\right]\ , \tag{2.3c}$$

$$\omega = \omega_0 + k\, A_e(u)\ , \tag{2.3d}$$

and u is the function of T defined by solving the Kepler equation

$$u - e\sin u = 2\pi\left[\left(\frac{T - T_0}{P_b}\right) - \frac{1}{2}\dot{P}_b\left(\frac{T-T_0}{P_b}\right)^2\right]\ . \tag{2.3e}$$

BINARY PULSAR TESTS OF STRONG FIELD / RADIATIVE

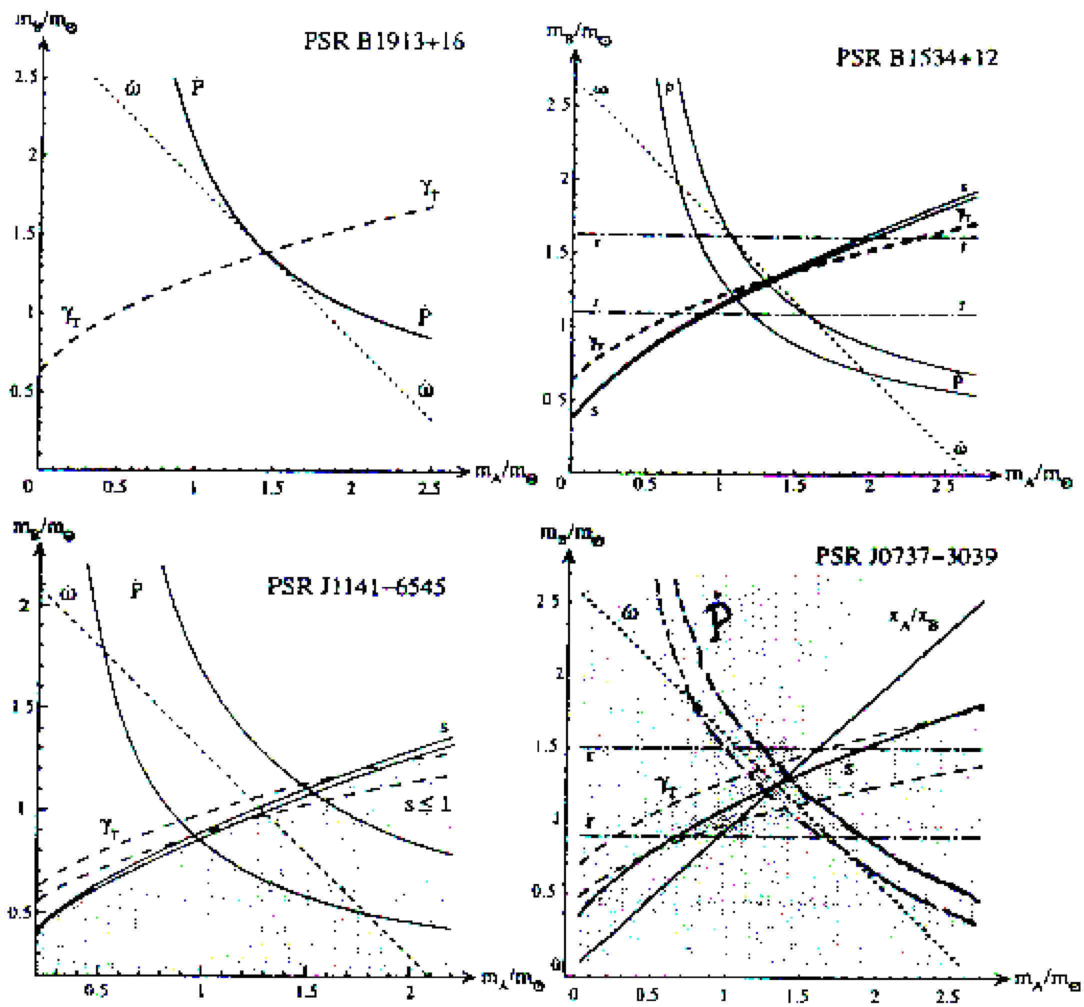
$3 - 2 = 1$

1 RADIATIVE + STRONG-FIELD $\sim 10^{-3}$ TEST

$5 - 2 = 3$

1 RAD. + STRONG FIELD

2 PURE STRONG-FIELD TESTS $\sim 10^{-2}$



$4 - 2 = 2$

1 RAD. + STRONG F

1 STRONG FIELD

$6 - 2 = 4$

3 STRONG FIELD TESTS

1 RAD. + STRONG FIELD

SOME HIGH-PRECISION BINARY-PULSAR TESTS

1913+16:

Weisberg, Taylor '04

Damour Taylor '91 $14\sigma^{OBS}$ CORRECTION

$$\frac{\dot{P}_b^{OBS} - \dot{P}_b^{GALACTIC}}{\dot{P}_b^{GR}\left[k^{OBS}, \gamma^{OBS}_{TIMING}\right]} = 1.0013 \pm 0.0021$$

1534+12:

Taylor, Wolszczan, Damour, Weisberg '92
Stairs et al. '02

$$\frac{s^{OBS}}{s^{GR}\left[k^{OBS}, \gamma^{OBS}_{TIMING}\right]} = 1.000 \pm 0.007$$

0737-3039

Lyne et al. '04, Kramer et al '04

$$\frac{s^{OBS}}{s^{GR}\left[k^{OBS}, R^{OBS}\right]} = 0.9998^{+0.0006}_{-0.0011}$$

RADIATIVE AND STRONG-FIELD EINSTEIN GRAVITY OK AT

10^{-3} LEVEL

FIRST APPROACH TO THEORY-DEPENDENT ANALYSIS

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

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

MAIN FIRST-ORDER CORRECTIONS PARAMETRIZED BY :

$$\boxed{\begin{array}{l} \bar{\gamma} \equiv \gamma^{PPN} - 1 \\ \bar{\beta} \equiv \beta^{PPN} - 1 \end{array}}$$

$\bar{\gamma}$: LIGHT DEFLEXION

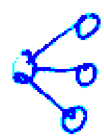
$\bar{\beta}$: PERIASTRON PRECESSION

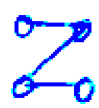
? GENERALIZATION OF $\bar{\beta}$ AND $\bar{\gamma}$ TO SECOND-ORDER CORRECTIONS $\propto \left(\frac{GM}{c^2 r}\right)^2$?

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)

$$\boxed{\begin{array}{c} \epsilon \\ \zeta \end{array}}$$


$\sim \beta' \alpha^3$


$\sim \alpha \beta \beta \alpha$

E.G.
EFFECTIVE GRAVITATIONAL COUPLING BETWEEN A and B

1PN (Nordtvedt '68)

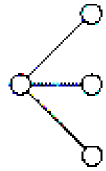
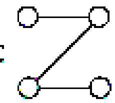
2PN (Damour, Esposito-Farèse '96)

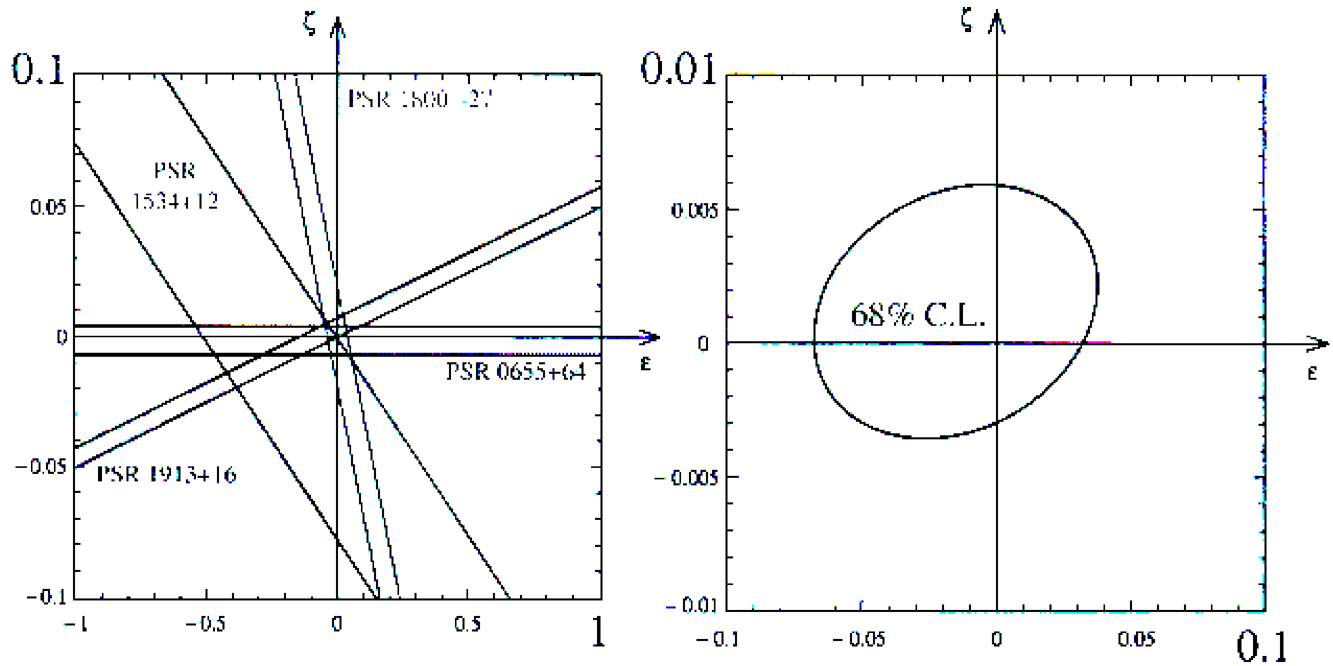
$$\boxed{\frac{G_{AB}}{G} = 1 + (4\bar{\beta} - \bar{\gamma})\left(\frac{E_A^{grav}}{m_A c^2} + \frac{E_B^{grav}}{m_B c^2}\right) + 4\zeta\left(\frac{E_A^{grav}}{m_A c^2}\right)\left(\frac{E_B^{grav}}{m_B c^2}\right) + \left(\frac{\epsilon}{2} + \zeta\right)\frac{\langle U^2\rangle_A + \langle U^2\rangle_B}{c^4} + \ldots}$$

- 2PN TERMS, $\propto \epsilon, \zeta$, ARE TOO SMALL TO BE MEASURABLE IN SOLAR SYSTEM
[THEY DO NOT ENTER LIGHT DEFLECTION !]

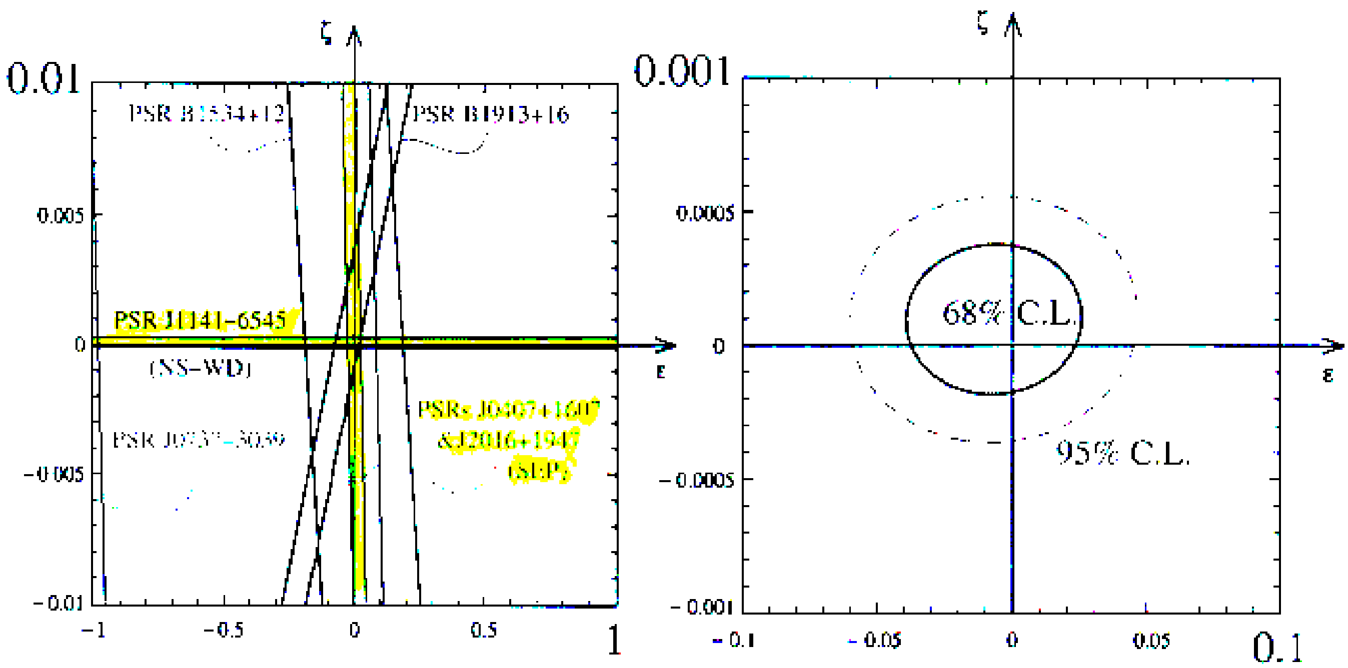
- BINARY PULSARS : $\frac{E_A^{grav}}{m_A c^2} \simeq 0.15$ $\Rightarrow$ ANALYZE DATA AS CONSTRAINTS ON ϵ, ζ

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

$-4 \times 10^{-2} < \varepsilon < 3 \times 10^{-2}$ $\quad -2 \times 10^{-4} < \zeta < +4 \times 10^{-4}$

SECOND APPROACH TO PROBING GRAVITY WITH BINARY PULSAR DATA :

(2) THEORY-DEPENDENT ANALYSIS OF PSR DATA

CHOOSE A CLASS OF SIMPLE ALTERNATIVES TO GR CONTAINING A SMALL NUMBER OF PARAMETERS, BUT SUFFICIENTLY MANY TO EXHIBIT INTERESTING EFFECTS

TENSOR-SCALAR GRAVITY :

$$S = \frac{1}{16\pi G}\int d^4x \sqrt{g}\left[R(g) - 2(\partial_\mu \varphi)^2\right] + S_{MATTER}\left[\psi;\ \tilde{g}_{\mu\nu} = e^{2a(\varphi)} g_{\mu\nu}\right] - \int d^4x \sqrt{g}\, V(\varphi)$$

SCALAR FIELD φ COUPLING FUNCTION $a(\varphi)$ POTENTIAL : FIXES φ_0

TWO-PARAMETER COUPLING FUNCTION

$$\boxed{a(\varphi) = \alpha_0 (\varphi - \varphi_0) + \frac{1}{2}\beta_0 (\varphi - \varphi_0)^2}$$

- SIMPLE GENERALIZATION OF JORDAN-FIERZ-BRANS-DICKE

$$a^{JFBD}(\varphi) = \alpha_0 (\varphi - \varphi_0) \quad ; \quad \alpha_0^2 \equiv \frac{1}{2\omega + 3}$$

- MINIMAL THEORY LEADING TO PPN PARAMETERS (Eddington, Nordtvedt, Will...

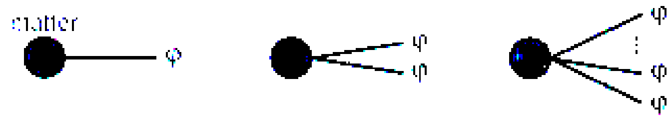
$$\boxed{\gamma^{PPN} - 1 = -2\frac{\alpha_0^2}{1+\alpha_0^2}} \quad ; \quad \boxed{\beta^{PPN} - 1 = \frac{1}{2}\frac{\beta_0 \alpha_0^2}{(1+\alpha_0^2)^2}}$$

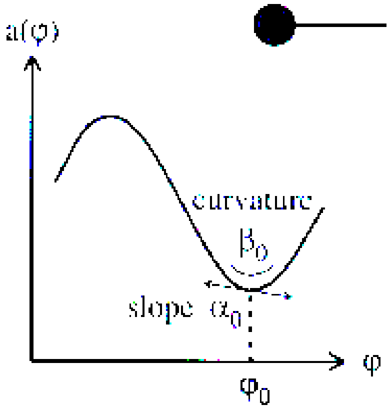
- FEATURES INTERESTING NON-PERTURBATIVE STRONG-FIELD EFFECTS

Tensor–scalar theories

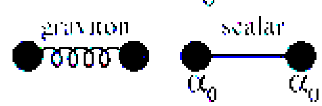
$$S = \frac{1}{16\pi G}\int \sqrt{-g}\,\Big\{\underset{\substack{\uparrow\\ \text{spin 2}}}{R} - 2\,\underset{\substack{\uparrow\\ \text{spin 0}}}{(\partial_\mu\varphi)^2}\Big\} + S_{\text{matter}}\Big[\text{matter}\,;\ \underset{\substack{\uparrow\\ \textbf{physical metric}}}{\tilde g_{\mu\nu}} \equiv e^{2a(\varphi)}\,g_{\mu\nu}\Big]$$

$$a(\varphi) = \alpha_0\,(\varphi-\varphi_0) + \frac{1}{2}\,\beta_0\,(\varphi-\varphi_0)^2 + \ldots$$



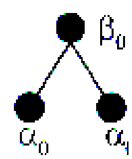


$$G_{\text{eff}} = G\,(1 + \alpha_0^2)$$

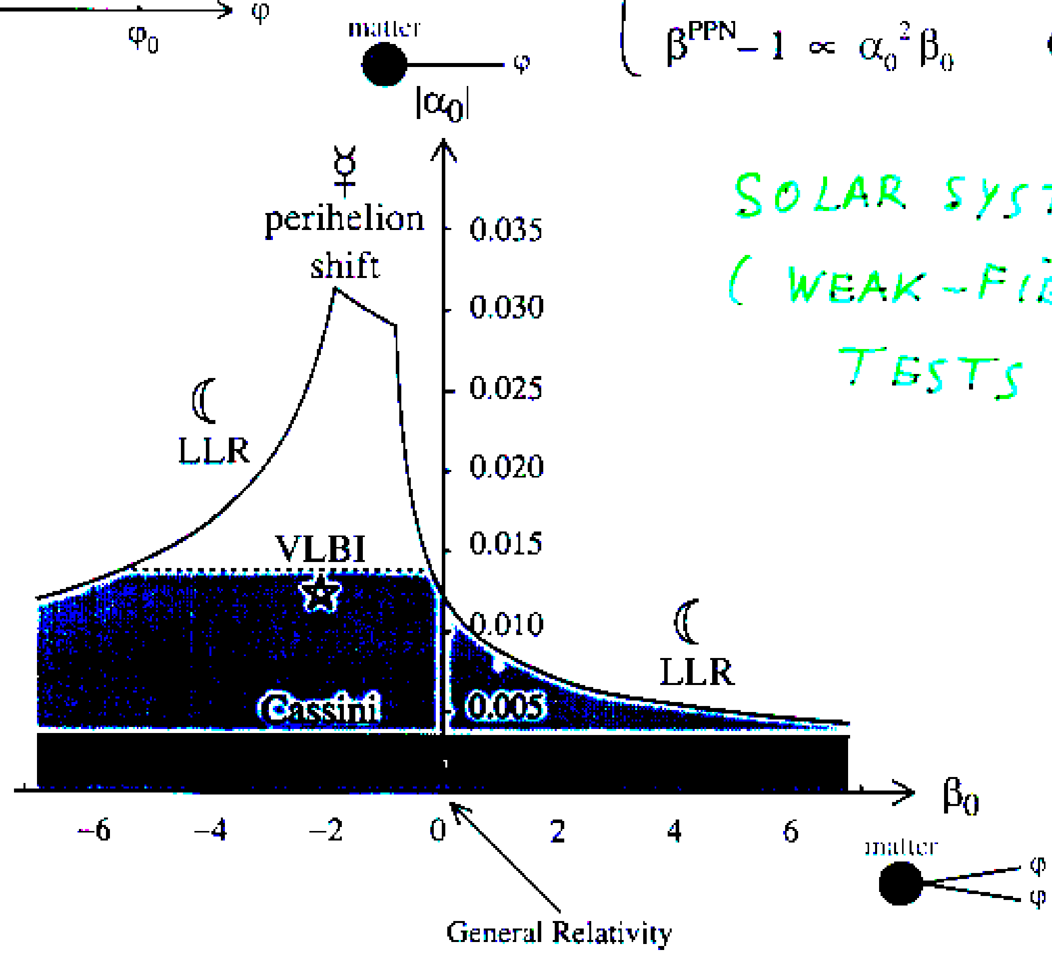


$$\gamma^{PPN} - 1 \propto \alpha_0^2$$

$$\beta^{PPN} - 1 \propto \alpha_0^2\,\beta_0$$

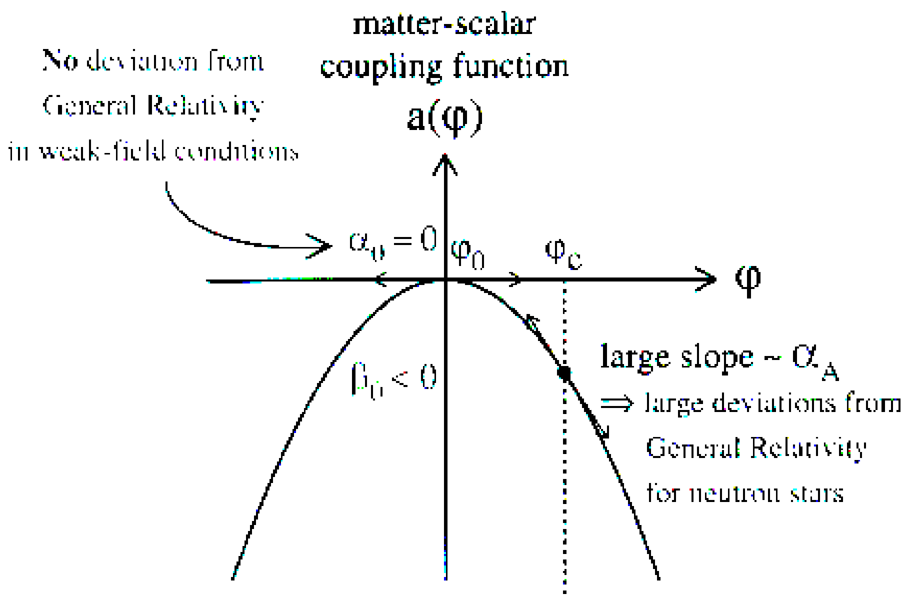


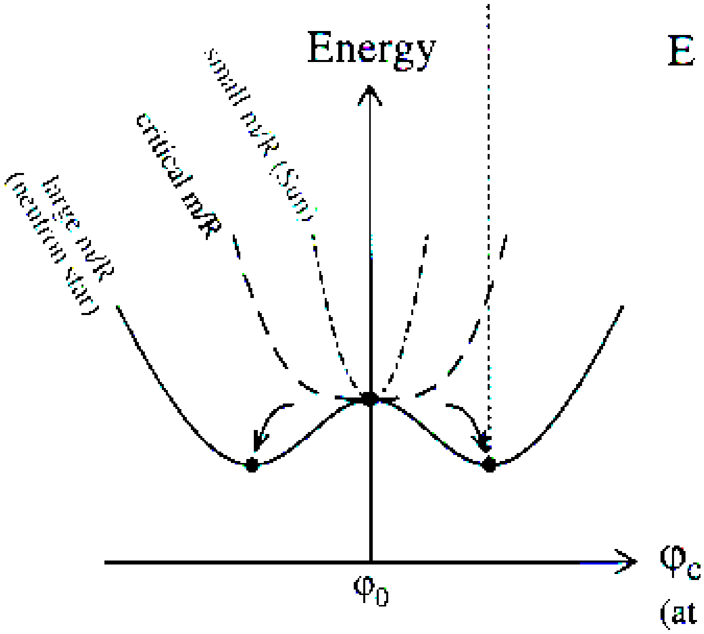
SOLAR SYSTEM
(WEAK-FIELD)
TESTS



Vertical axis ($\beta_0 = 0$) : Jordan–Fierz–Brans–Dicke theory $\alpha_0^2 = \dfrac{1}{2\,\omega_{BD} + 3}$

NON-PERTURBATIVE STRONG-FIELD EFFECTS





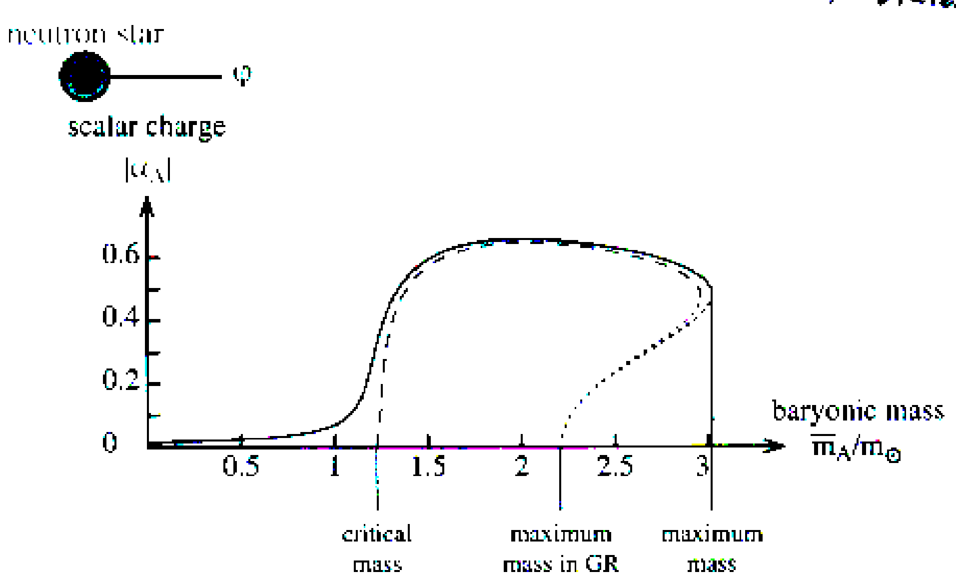
$$E \approx \int \left[\tfrac{1}{2} (\vec{\nabla}\varphi)^2 + \rho\, e^{\beta_0 \varphi^2/2} \right]$$

$$\downarrow \qquad\qquad \downarrow$$

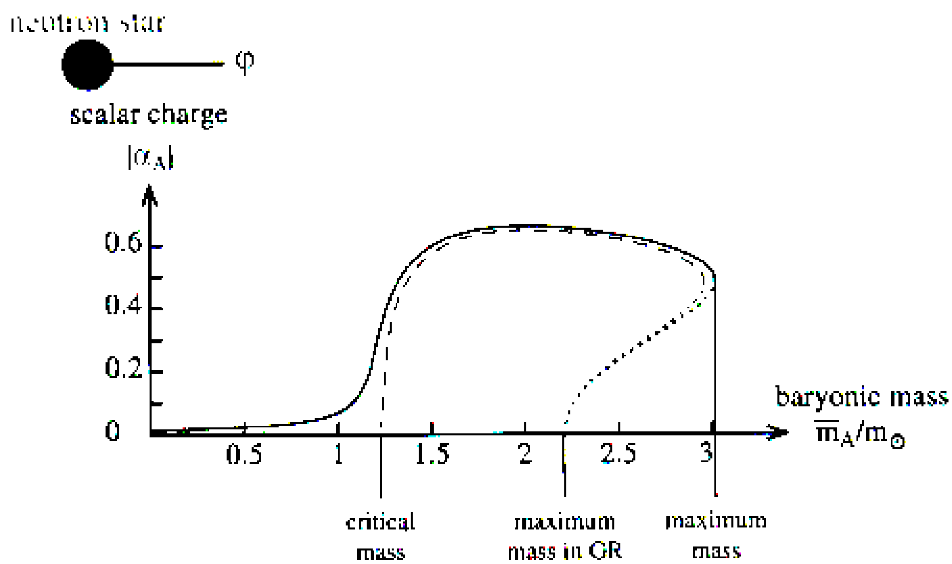
$$\tfrac{1}{2} R\, \varphi_c^{\,2} \;+\; m\, e^{\beta_0 \varphi_c^2/2}$$

parabola   Gaussian if $\beta_0 < 0$

"spontaneous scalarization" [T. Damour & G.E. Spósito Farèse 1993]

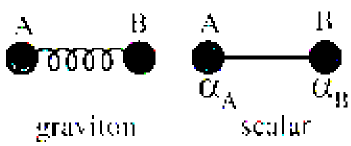


Strong-field effects

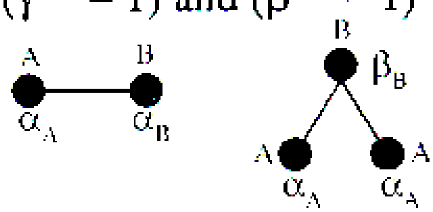


$$G_{AB}^{\text{eff}} = G\ (1 + \alpha_A \alpha_B)$$

depends on internal structure of bodies A & B

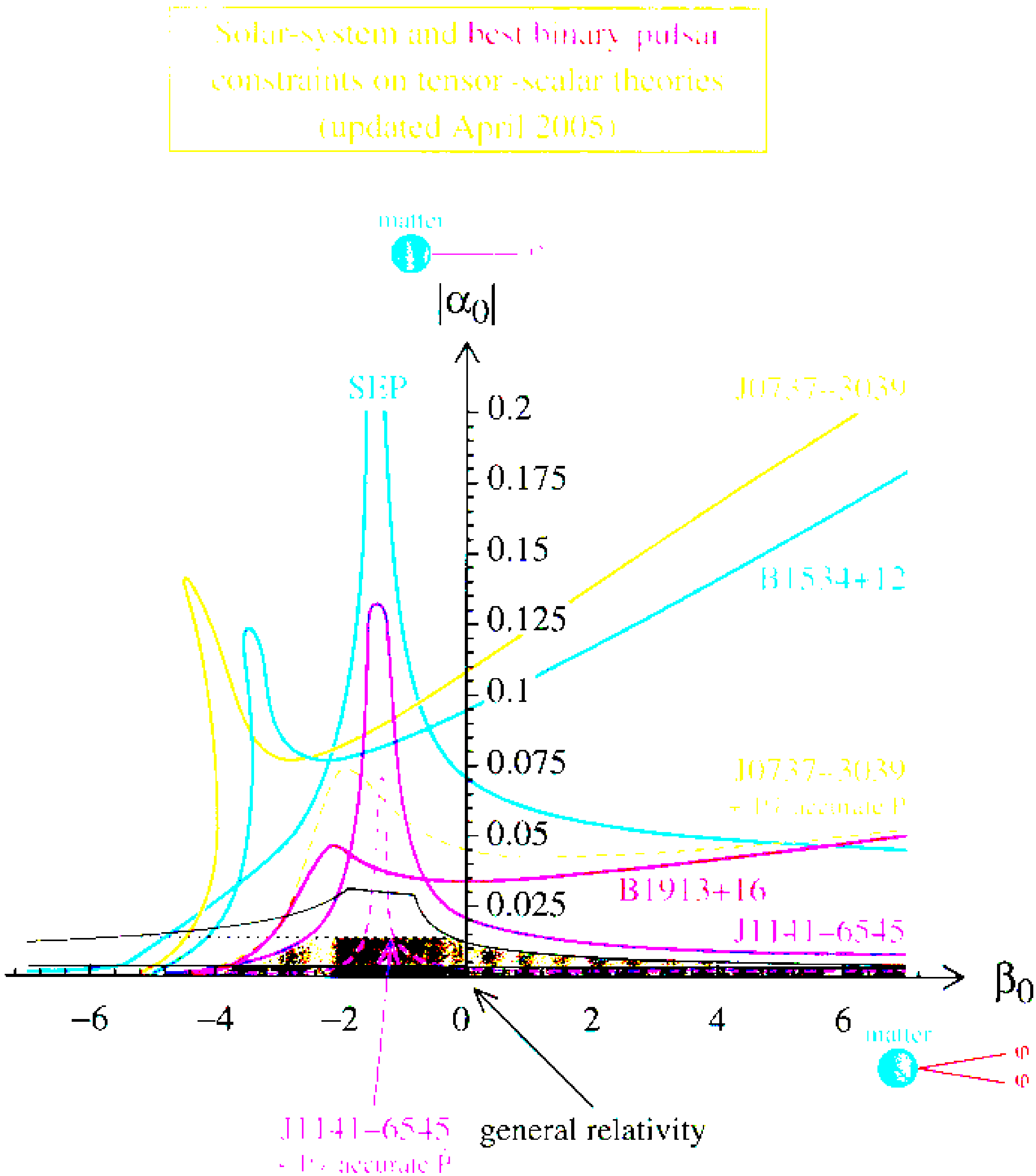


similarly for $(\gamma^{\text{PPN}} - 1)$ and $(\beta^{\text{PPN}} - 1)$ $\Rightarrow$ all post-Newtonian effects



$$\text{Energy flux} = \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \qquad \text{spin 2}$$

$$+ \frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \underbrace{\frac{\text{Dipole}}{c^3}}_{\propto(\alpha_A - \alpha_B)^2} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \qquad \text{spin 0}$$


Solar-system and best binary pulsar
constraints on tensor-scalar theories
(updated April 2005)
matter
$|\alpha_0|$
SEP
J0737-3039
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
B1534+12
J0737-3039
B1913+16
J1141-6545
β_0
−6
−4
−2
0
2
4
6
matter
J1141-6545
general relativity

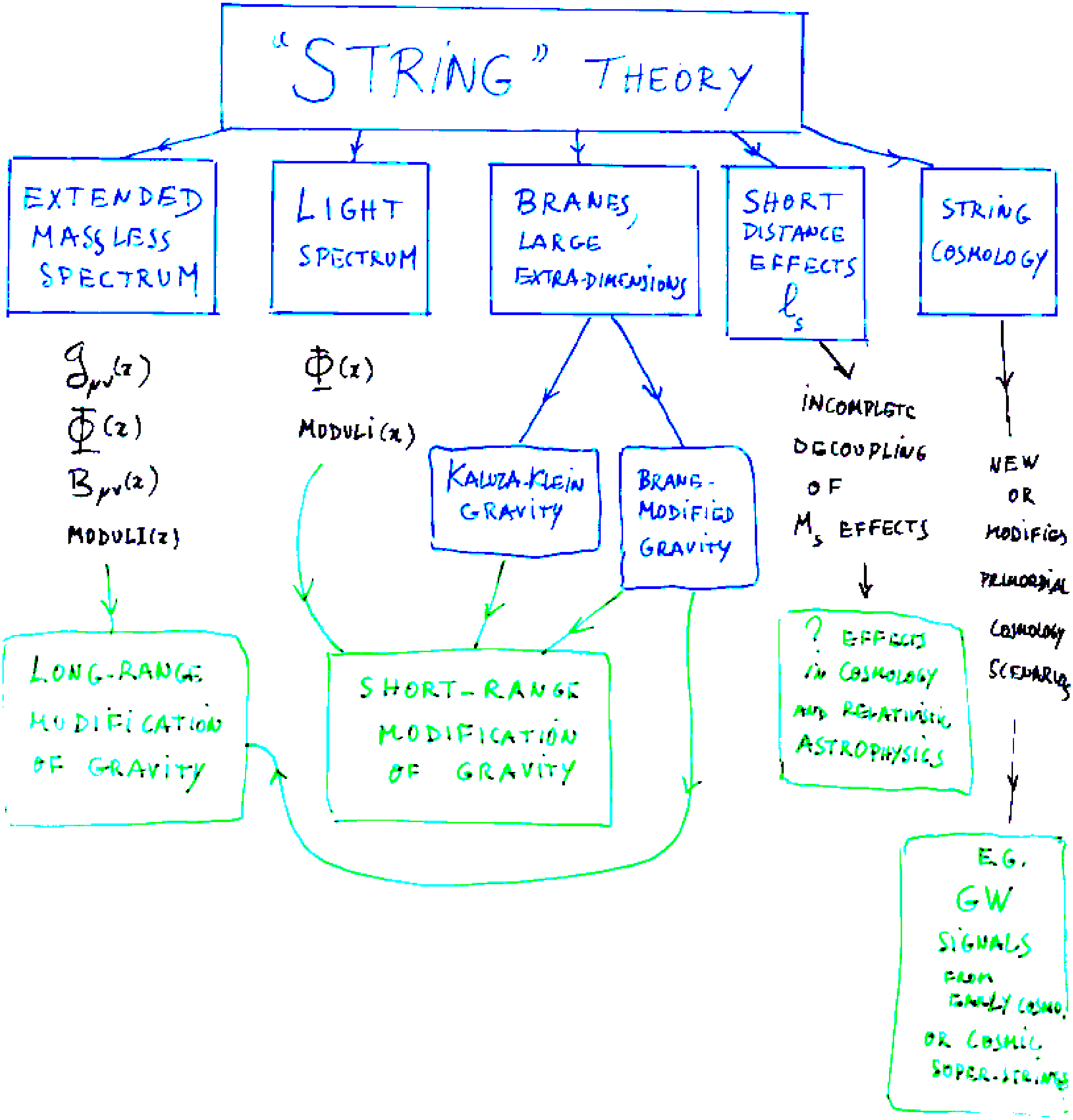
WAS EINSTEIN 100% RIGHT?

SHOULD WE STOP TESTING SPECIAL AND GENERAL RELATIVITY?

STRING-INSPIRED PHENOMENOLOGY

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

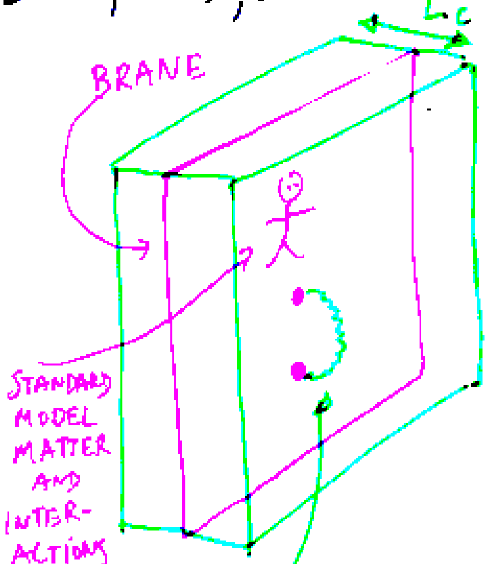
⇒ DISCUSS PHENOMENOLOGICAL POSSIBILITIES ; OPEN NEW EXPERIMENTAL OPPORTUNITIES



BRANES AND GRAVITY

"LARGE" BUT COMPACT EXTRA-DIMENSIONS

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali



BULK GRAVITY

$\Downarrow$

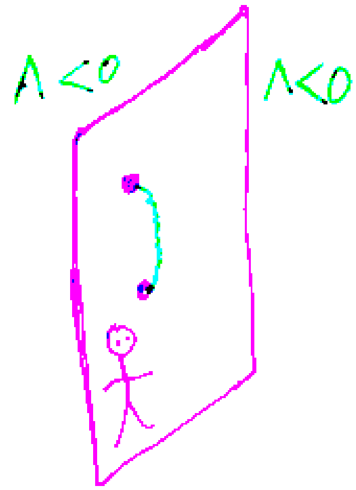
HIGHER-DIMENSIONAL GRAVITY WHEN

$$r < L_c$$

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

INFINITE EXTRA-DIMENSIONS BUT "MISMATCHED" GRAVITY

Randall, Sundrum



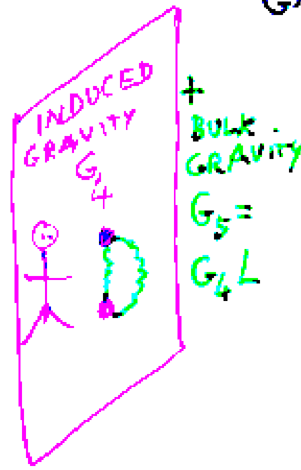
GRAVITY ≈ SURFACE WAVE

$\Downarrow$

MODIFICATION OF GRAVITY WHEN

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

Dvali Gabadadze Porrati



GRAVITY = SURFACE ⊕ BULK PROPAGATION

$\Downarrow$

MODIFICATION OF GRAVITY WHEN

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

AND SMALL MODIFICATIONS FOR $r < L$

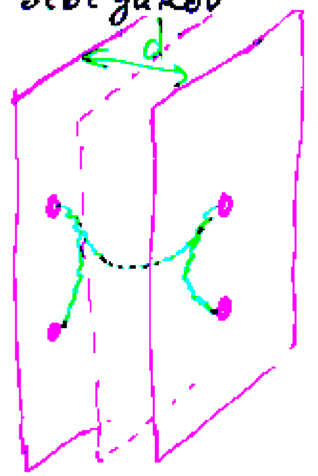
Dvali, Gruzinov, Zaldarriaga

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

EFFECTS IN SOLAR SYSTEM, LUNAR RANGING...

MULTI-BRANES

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



TUNNELLING (EVANESCENT WAVE) BETWEEN SEVERAL GRAVITON WAVES

$\Downarrow$

MULTI-GRAVITY

$\Downarrow$

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

INVERSE SQUARE LAW TESTS

(Adelberger, Heckel, Nelson '03)

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

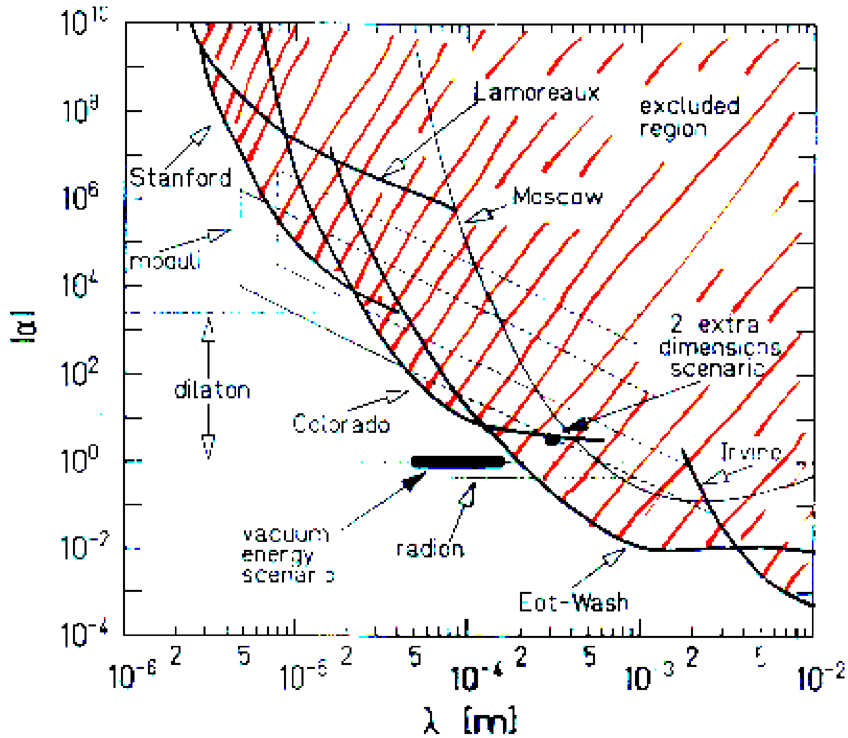


Figure 5: 95% confidence-level constraints on ISL violating Yukawa interactions with 1 μm $< \lambda <$ 1 cm. The heavy curves give experimental upper limits (the Lamoreaux constraint was computed in Reference (151)). Theoretical expectations for extra dimensions (56), moduli (101), dilaton (102), and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

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

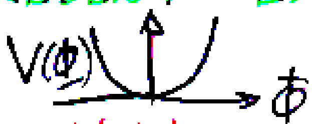
	GEOMETRY	COUPLING CONSTANTS	
NEWTON	RIGID	RIGID	
EINSTEIN	SOFT	RIGID	EINSTEIN EQUIVALENCE PRINCIPLE
STRING THEORY	SOFT	SOFT	VIOLATION OF THE EQUIVALENCE PRINCIPLE

$$\boxed{\underset{\text{geometry}}{g} \sim \underset{\text{gravitation}}{g} \sim \underset{\text{gauge coupling constant}}{g} \sim \underset{\text{gravitational coupling constant}}{G} \qquad g_{\mu\nu}(x) \sim g^2(x) \sim G(x)}$$

BUT THEN ONE WOULD EXPECT:

- NON-UNIVERSALITY OF FREE FALL $\quad \frac{\Delta a}{a} \sim 10^{-5}$
- COSMOLOGICAL VARIATION OF COUPLING CONSTANTS
$$\frac{\dot{\alpha}}{\alpha} \sim \frac{\dot{\mu}}{\mu} \sim H_0 \sim 10^{-10}\,\mathrm{yr}^{-1}$$
- 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

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

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: $V(\Phi) \sim M_{SUSY}^4\, \mathcal{V}\left(\frac{\Phi}{\tilde{m}_P}\right)$

$$\Rightarrow m_\Phi \sim \frac{m^2_{SUSY}}{\tilde{m}_P} \overset{?}{\sim} \frac{(1\ \mathrm{TeV})^2}{2.4 \times 10^{18}\,\mathrm{GeV}} \sim 10^{-3}\,\mathrm{eV}$$

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

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

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

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

$\Downarrow$

$V_{EFF}(\Phi)$ 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 $B(\Phi)$

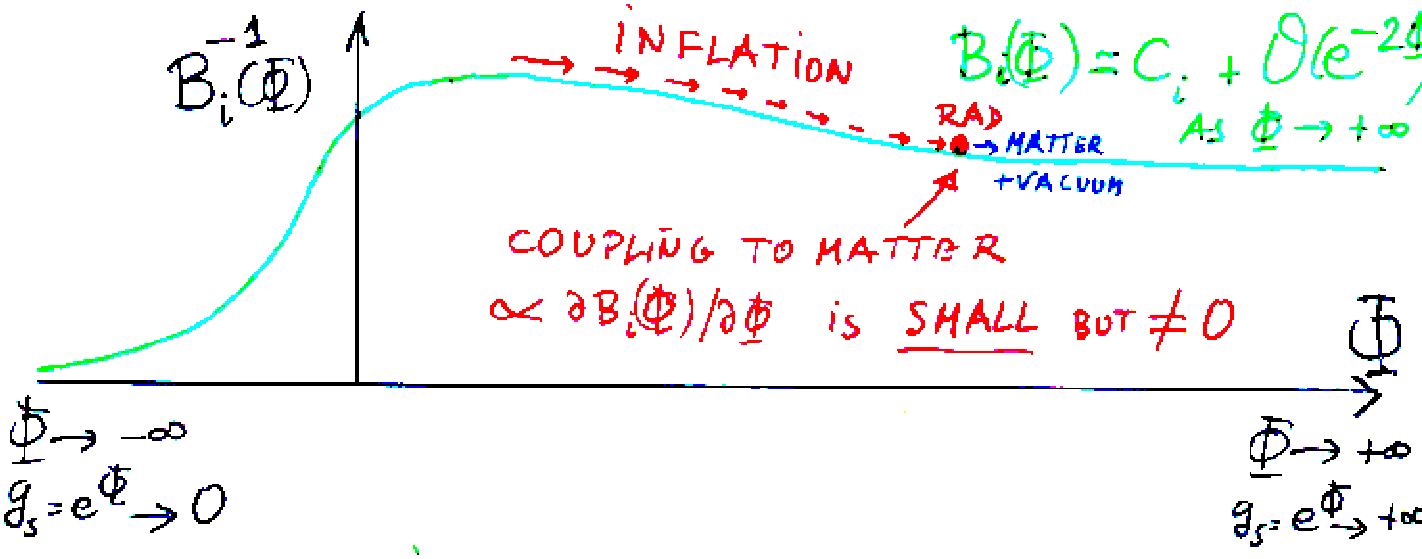
$\Rightarrow m_\Phi$ DEPENDS ON SURROUNDING MATTER DENSITY SO THAT Φ IS SHORT-RANGED IN EARTH-BOUND EXPTS Khoury, Weltman; Brax, ...

ATTRACTOR SCENARIO, WITH RUN-AWAY

Damour, Polyakov ; Damour, Piazzo, Veneziano

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

DILATON COUPLING FUNCTIONS



$B_i(\Phi) = C_i + \mathcal{O}(e^{-2\Phi})$ AS $\Phi \to +\infty$

OBSERVATIONAL CONSEQUENCES TODAY

RESIDUAL COUPLING

$$\alpha^2_{had}(\Phi_{end}) \sim 10\left(\frac{b_F}{b_\lambda C}\right)^2\left(\frac{\delta\rho}{\rho}\right)^{\frac{8}{n+2}} \sim 2.5\times 10^{-8}$$

$V(\chi) \sim \chi^n$ IF $n=2$

$$\Rightarrow \quad \gamma^{PPN} - 1 \simeq -2\alpha^2_{had} \sim -5\times 10^{-8}$$

$$\frac{\Delta a}{a} \sim 5\times 10^{-5}\,\alpha^2_{had} \sim 10^{-12}$$

$$\frac{\dot{\alpha}_{EM}}{\alpha_{EM}} \sim \pm\sqrt{1+q_0-\frac{3\Omega_m}{2}}\,\sqrt{10^{12}\frac{\Delta a}{a}}\;10^{-16}\,yr^{-1}$$

FUTURE EXPERIMENTS ON GRAVITY

- GRAVITY PROBE B
- COMPARISON OF ATOMIC CLOCKS
- EXPLORING SUB-MICRON DEVIATIONS FROM NEWTON'S LAW
- OLD AND NEW BINARY PULSARS
- IMPROVED SOLAR-SYSTEM TESTS
  - MORE $\gamma-1 \sim 2.5\times10^{-6}$, $\beta-1 \sim 5\times10^{-6}$
  - GAIA (ESA, GLOBAL ASTROMETRY, 4-10 μarcsec) $\gamma-1 \sim 10^{-7}$
  - LATOR $\gamma-1 \sim 10^{-9}$
- 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

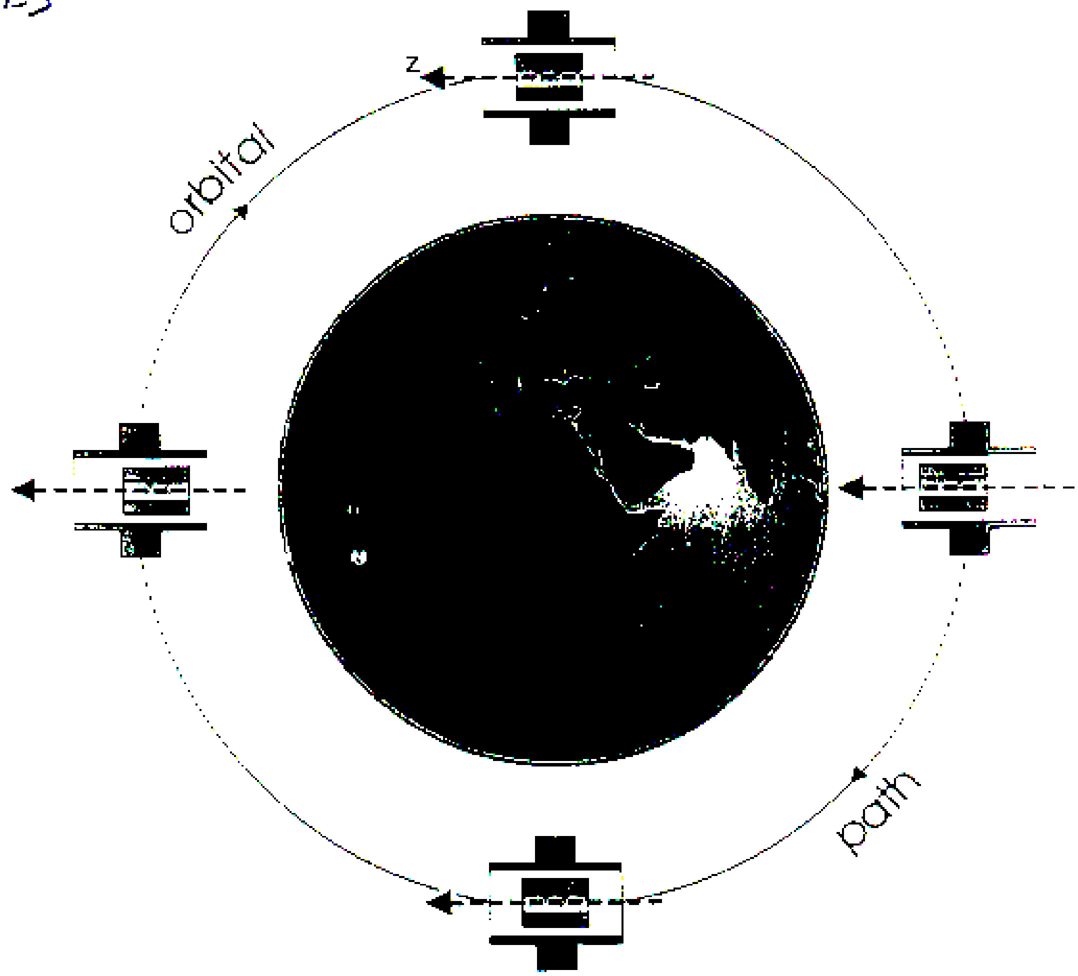
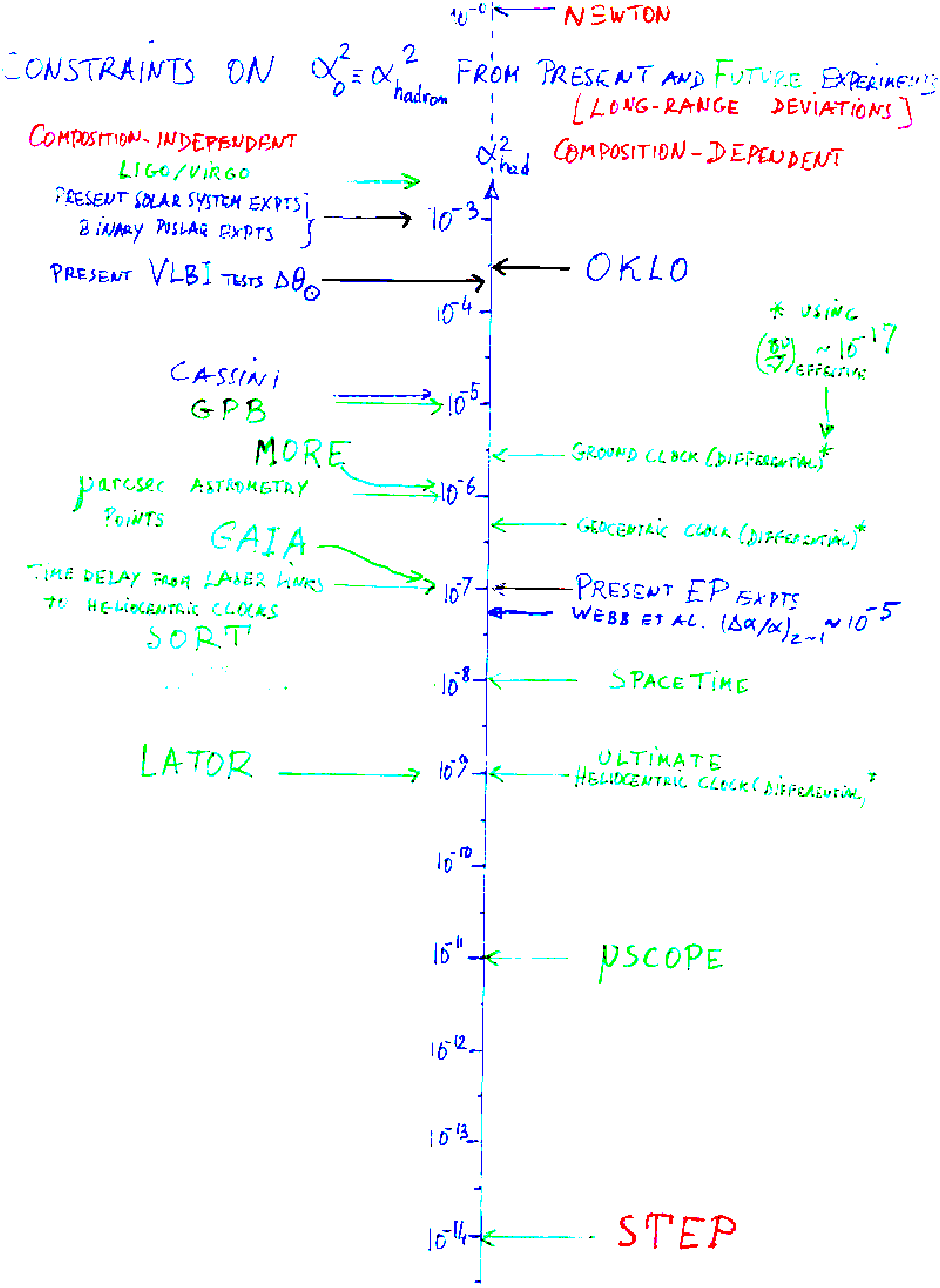
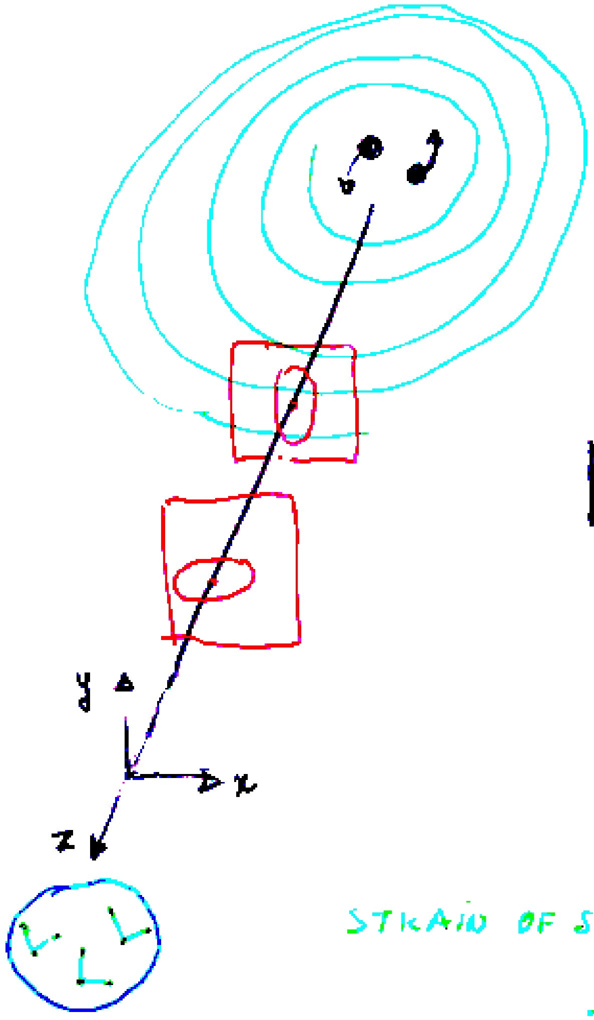


Fig. 3.2: *Equivalence principle violation:* ***The Figure shows the relative motion of free masses where the ratio of inertial mass to gravititional mass depends on the composition of the masses. These test masses are constrained by linear magnetic bearings and sensing circuits. Here, the Equivalence 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 $\mp$ the orbital frequency (depending on the spin sense).***



CONSTRAINTS ON $\alpha_0^2 \equiv \alpha_{hadron}^2$ FROM PRESENT AND FUTURE EXPERIMENTS
[LONG-RANGE DEVIATIONS]
10^{-0} NEWTON
COMPOSITION-INDEPENDENT
COMPOSITION-DEPENDENT
α_{had}^2
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
10^{-8}
SPACETIME
LATOR
10^{-9}
ULTIMATE HELIOCENTRIC CLOCK (DIFFERENTIAL)*
10^{-10}
10^{-11}
μSCOPE
10^{-12}
10^{-13}
10^{-14}
STEP

GRAVITATIONAL RADIATION



EXCITATION OF SPACETIME GEOMETRY

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

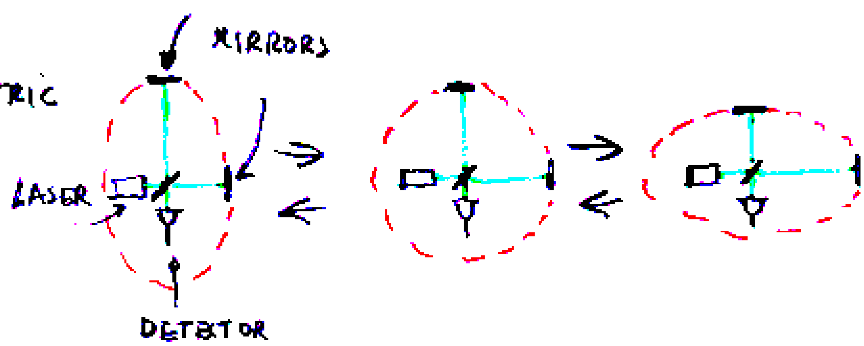
$$h_{\mu\nu} = \begin{array}{c} \begin{array}{cccc} t & x & y & z \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

TWO TRANSVERSE POLARIZATIONS

STRAIN OF SPACE DISTANCES:

$$\frac{\delta L}{L} \sim h$$

INTERFEROMETRIC DETECTOR



∃ SEVERAL INDEPENDENT OBSERVATIONAL PROOFS OF REALITY OF GRAV. RADIATION

PSR 1913+16 0.3% PROOF THAT $c_g = c$ $t - d/c_g$

+ PSR 1534+12, PSR J1141−6545, PSR J0737−3039

+ PSR 1913+16 NS

$\frac{2GM}{c^2R} = 0.4 \Rightarrow$ 1% TEST OF STRONG-FIELD REGIME OF GENERAL RELATIVITY

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

66
OL16

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

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

with

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

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

"DRESSED MASSES" INCORPORATING STRONG-SELF-FIELD EFFECTS

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

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

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

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

and

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

GRAVITATIONAL RADIATION DAMPING

DIRECT EFFECT OF PROPAGATION OF GRAVITY AT SPEED C

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_e^{-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, $\bar{S}$, associated with $S_{\mu\nu}$, the law of evolution ('spin precession') reads for the first body (see also references in Section 6.13.2)

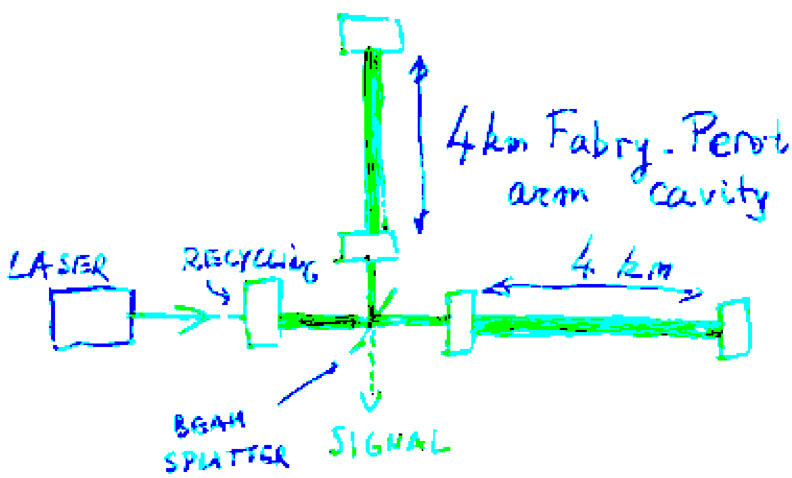
$$\frac{\mathrm{d}\bar{S}}{\mathrm{d}t} = \left[\frac{Gm'}{c^2R^2}\,\bar{N} \times \left(\frac{3}{2}\bar{v} - 2\bar{v}'\right)\right] \times \bar{S} + O\left(\frac{1}{c^4}\right). \quad (162)$$

GROUND-BASED NETWORK OF INTERFEROMETRIC DETECTORS

LIGO / VIRGO / GEO / TAMA / ...

2 SITES (Hanford, Livingston)	1 SITE	1 SITE	1 SITE
3 INTERFEROMETERS	1 INTERFEROMETER	1 INTERFERO	1 INTERF
4 km + 2 km, 4 km	3 km	600 m	300 m

NEED 3 SITES FOR LOCALIZING THE SOURCE

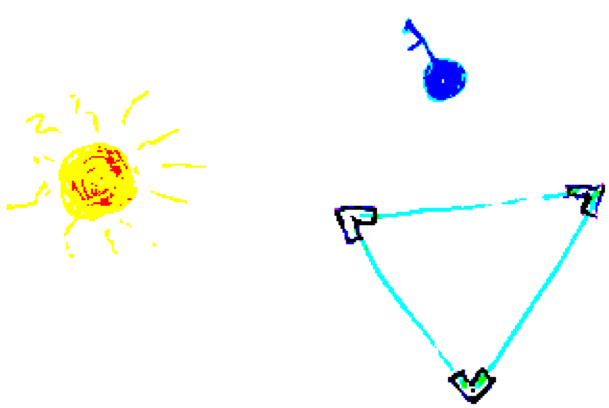


$$\frac{\delta L}{L} \sim h < 10^{-21}$$

$$\delta L < 4 \times 10^{-16}\ \text{cm}$$

SPACE-BASED INTERFEROMETRIC DETECTOR

LISA (ESA/NASA)



2 INTERFEROMETERS (ONE COMMON ARM)

$\sim 5 \times 10^6$ km arms

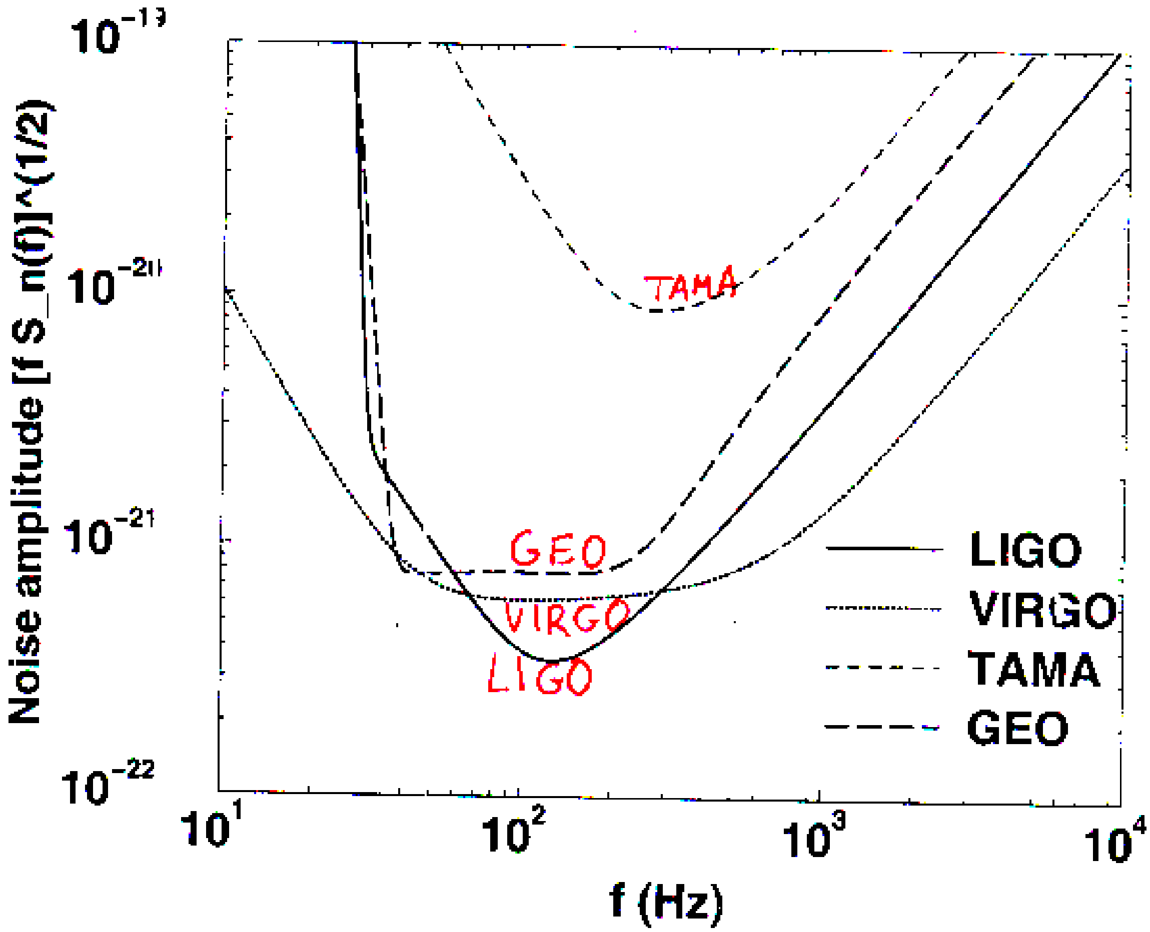
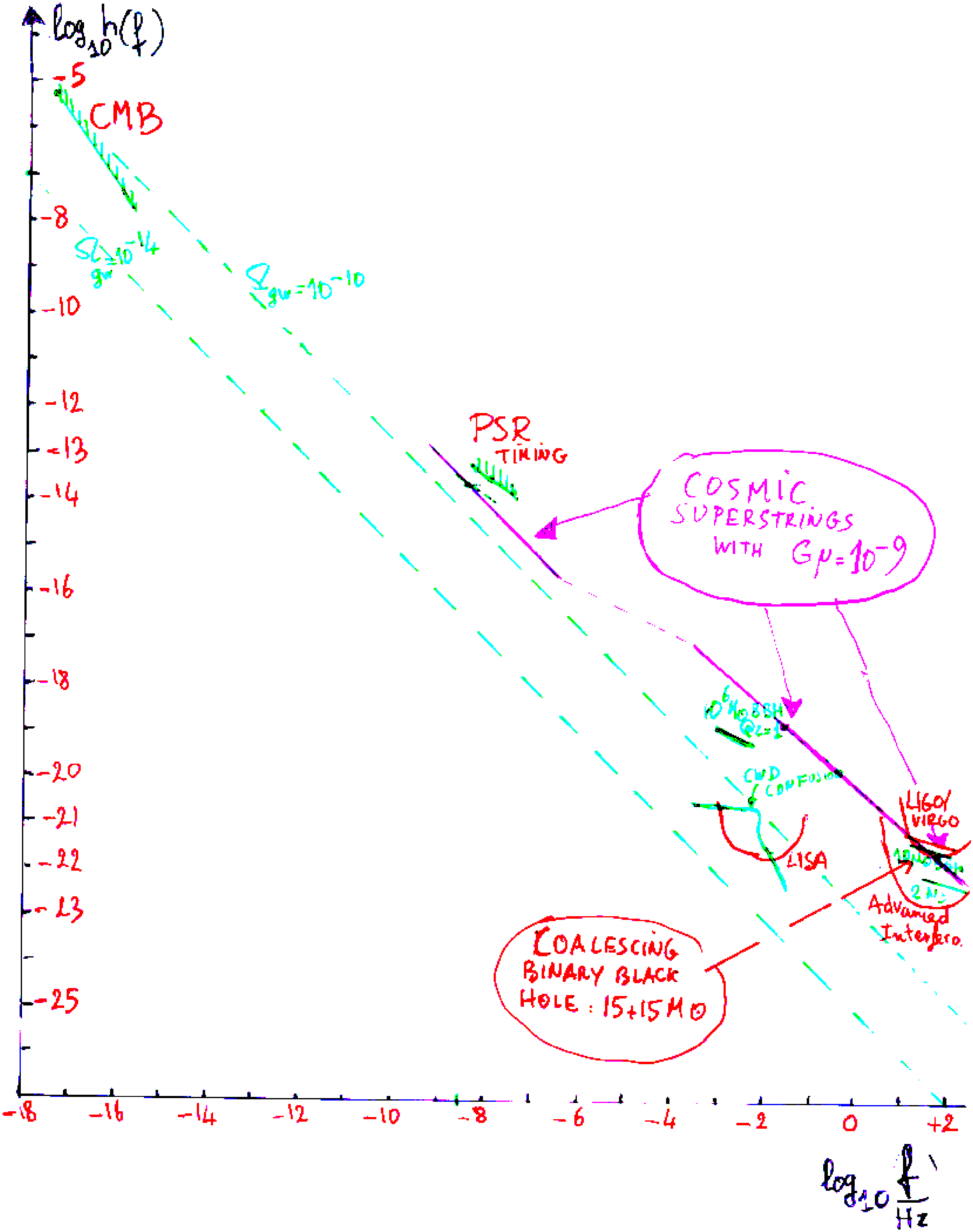


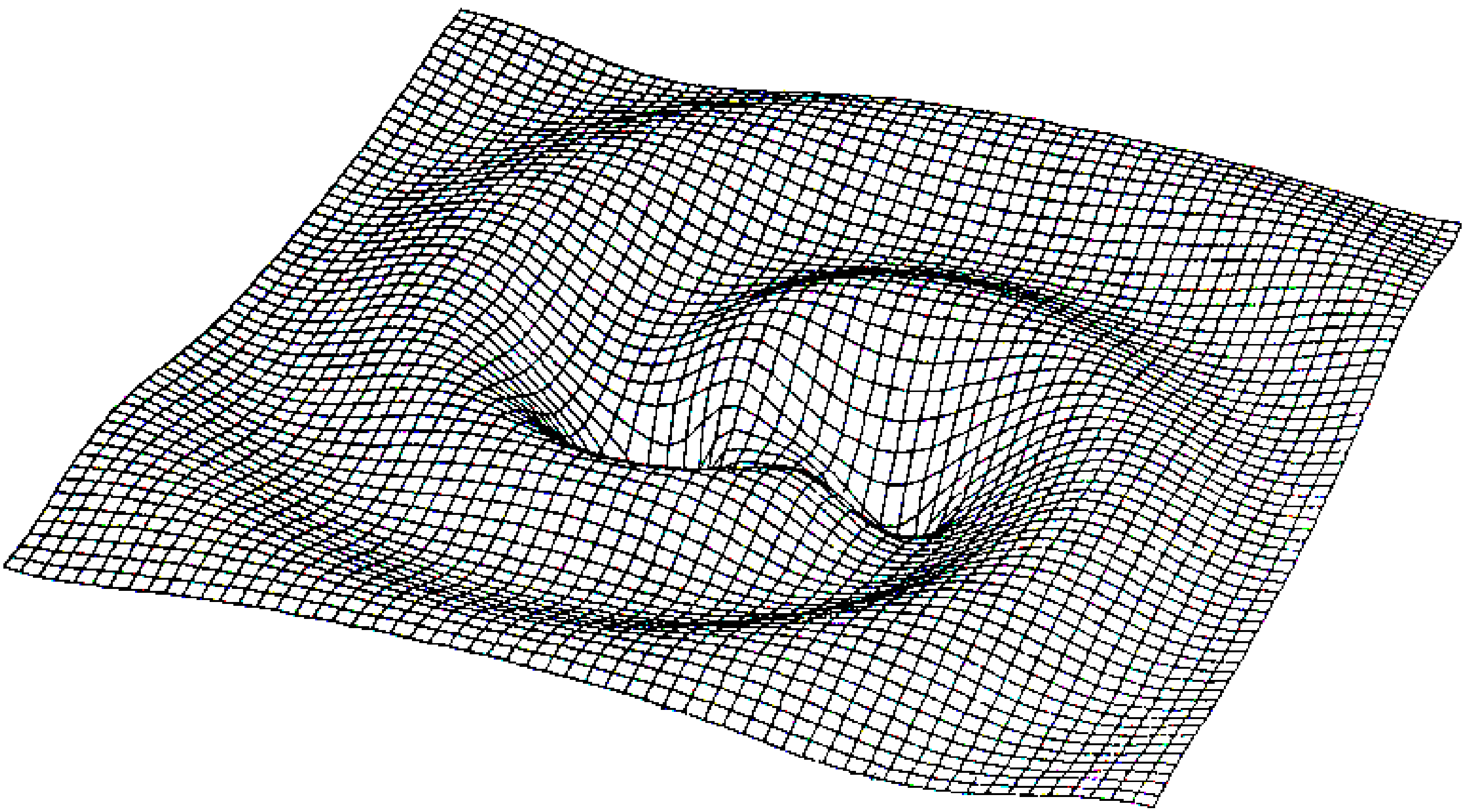
FIG. 3. The effective noise $h_n = \sqrt{f S_n(f)}$ in various ground-based interferometers.

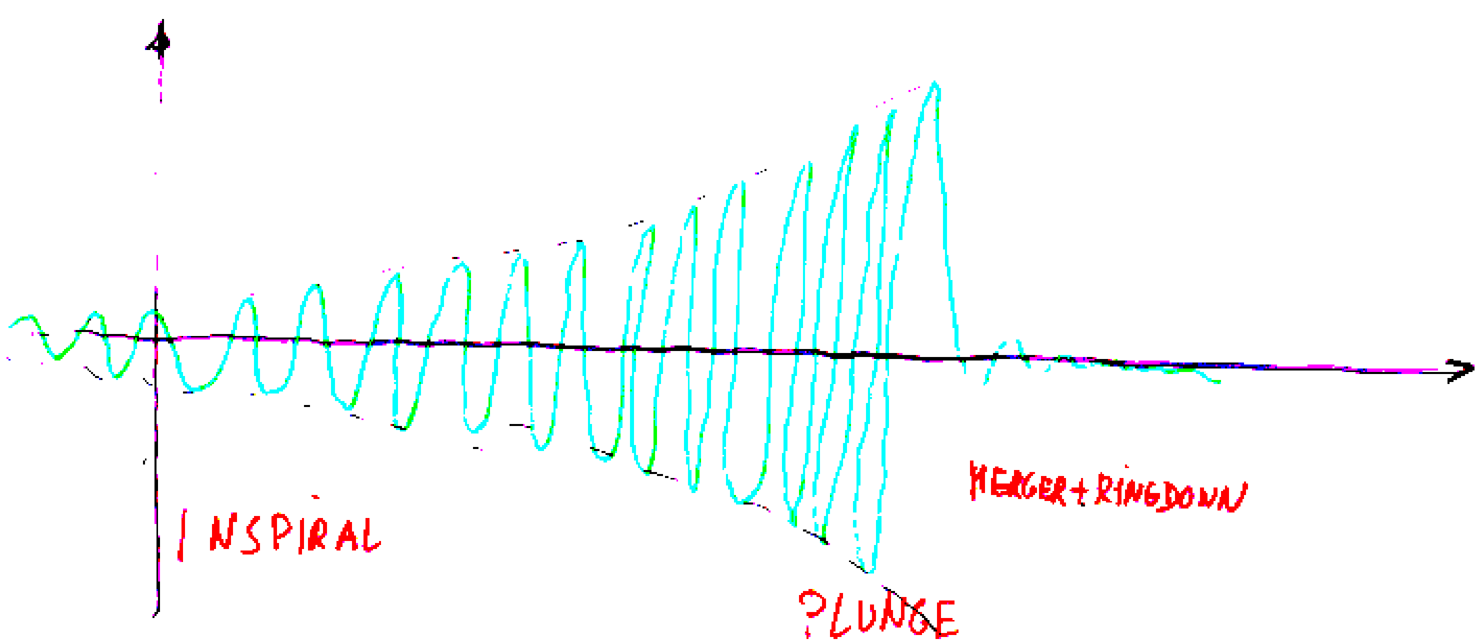
GW SPECTRUM



$\log_{10} h(f)$
-5
-8
-10
-12
-13
-14
-16
-18
-20
-21
-22
-23
-25
CMB
$\Omega_{gw} \geq 10^{-14}$
$\Omega_{gw} = 10^{-10}$
PSR
TIMING
COSMIC
SUPERSTRINGS
WITH $G\mu = 10^{-9}$
$10^6 M_\odot$ BBH @z=1
CWD
CONFUSION
LISA
LIGO/
VIRGO
Advanced
Interfero.
COALESCING
BINARY BLACK
HOLE : 15+15 $M_\odot$
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
$\log_{10} \frac{f}{Hz}$

COALESCING BINARY





COALESCING BINARY BLACK HOLE

$$m_1 + m_2 \sim 20 \text{ to } 30\, M_\odot$$

- EVENT RATE : ? ~ 1 / yr @ 200 Mpc (Lipunov, Postnov, Prokhorov '97 McMillan, Portegies Zwart '00, ...)

- THEORETICAL CHALLENGES

USEFUL SIGNAL COMES FROM LAST FEW ORBITS + PLUNGE
(Flanagan, Hughes '97, Damour, Iyer, Sathyaprakash '01)

$$f_{LSO}^{GW} = 2 f_{LSO}^{ORBIT} \sim 5000 \frac{M_\odot}{m_1+m_2}\,\mathrm{Hz} \simeq 167 \left(\frac{30 M_\odot}{m_1+m_2}\right) \mathrm{Hz}$$

- NEW ANALYTICAL METHODS :

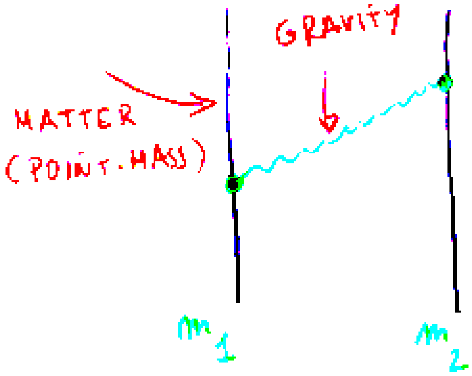
  - VERY HIGH-ORDER PERTURBATION CALCULATIONS OF DYNAMICS AND RADIATION : " 3 – LOOP "

WITH DIMENSIONAL REGULARIZATION (Damour, Jaranowski, Schäfer '01, Blanchet, Damour, Esposito-Farèse '04, Blanchet, Damour, Esposito-Farèse, Iyer, '05)

  - RESUMMATION OF PERTURBATIVE EXPANSIONS : PADÉ APPROXIMANTS (Damour, Iyer, Sathyaprakash)

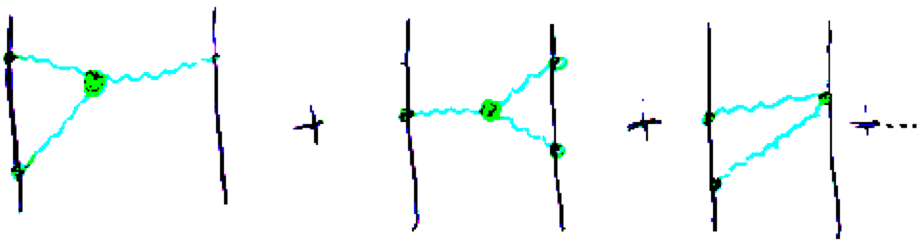
  - " EFFECTIVE ONE BODY " APPROACH (Buonanno, Damour)
[SIMILAR TO : QED etc (Brézin Itzykson Zinn-Justin, Todorov ...)]

"3-LOOP" CALCULATION OF 2 POINT-MASS GRAVIT. INTERACTION

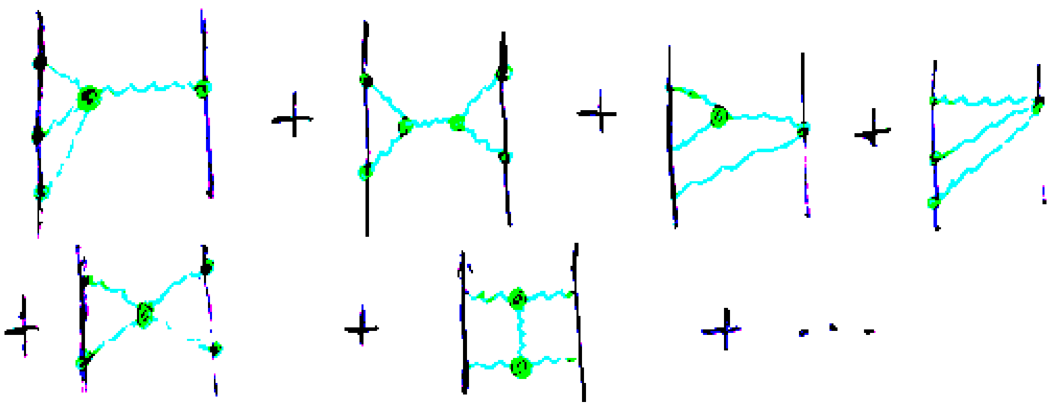


'ZERO-LOOP' = ONE-GRAVITON EXCHANGE

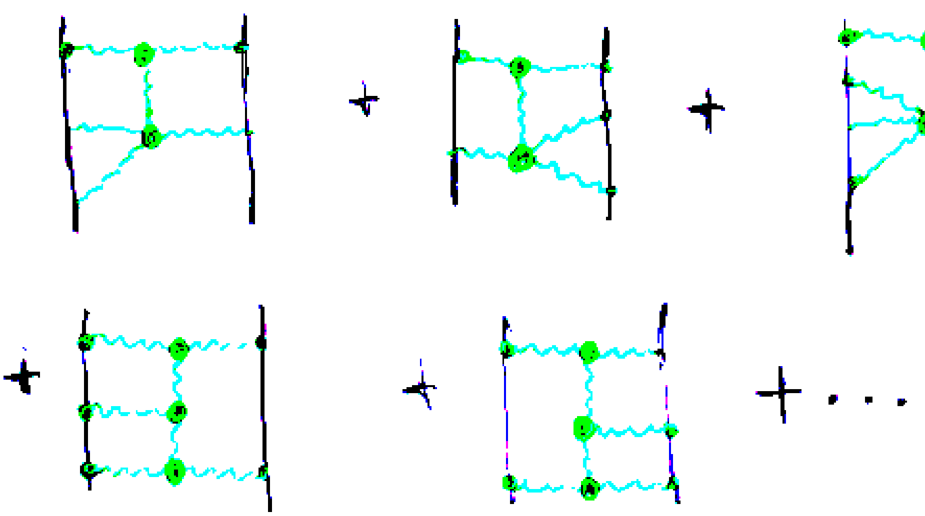
$$= -\frac{G m_1 m_2}{r_{12}}\left[1 + \frac{v^2}{c^2} + \frac{v^4}{c^4} + \dots\right]$$



'1-LOOP'



'2-LOOP'



'3-LOOP'

FINITE (UNAMBIGUOUS) RESULT IN DIMENSIONAL REGULARIZATION
(Damour, Jaranowski, Schäfer '01)

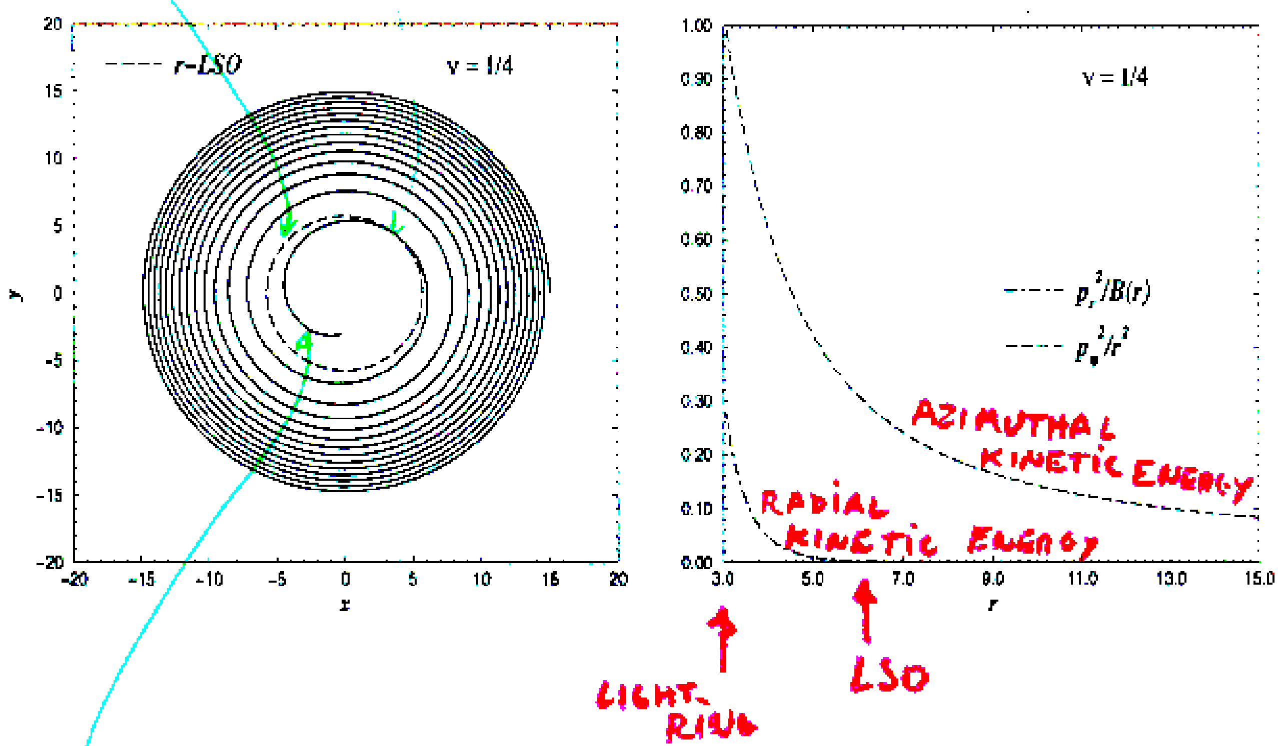
(RESUMMED) EFFECTIVE ONE BODY DYNAMICS T8/5

+ RESUMMED RADIATION REACTION (QUASI-CIRCULAR ORBIT

TRANSITION INSPIRAL → PLUNGE WITH ARBITRARY MASS RATIO

(1) YIELDS INITIAL DYNAMICAL DATA $(q_1 q_2\ p_1 p_2)$

AT BEGINNING OF PLUNGE: 0.6 ORBIT LEFT



REMAINS QUASI-CIRCULAR DURING THE WHOLE PLUNGE

(2) FIRST ESTIMATE OF FULL WAVEFORM: "6M" → "3M" ≃ MERGER

6

'RESTRICTED' WAVE FORM

$h(t) \equiv v_\omega^2 \cos 2\varphi(t)$

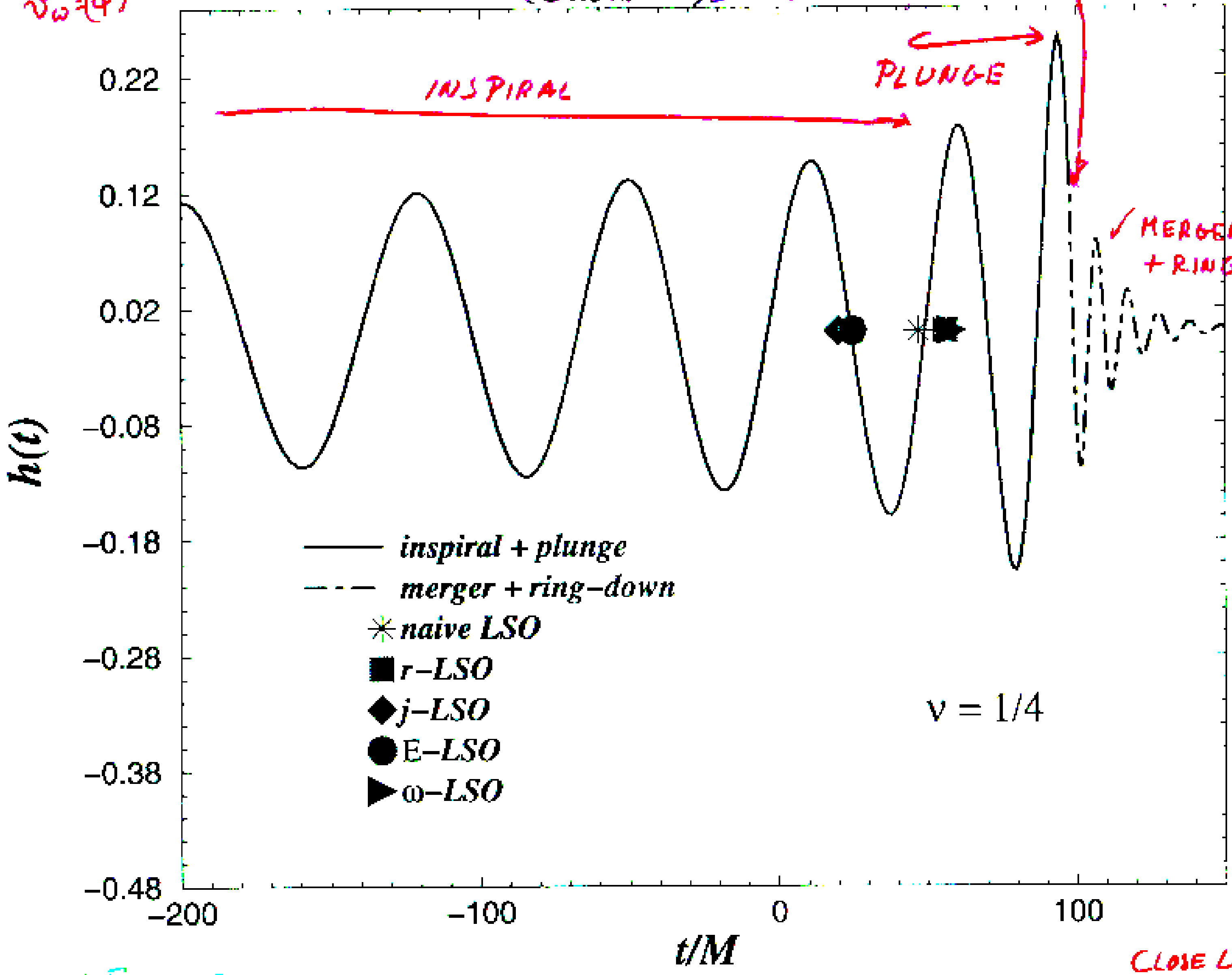
$v_\omega = (\dot\varphi)^{1/3}$

MATCHING TO LEAST-DAMPED QUASI-NORMAL-MODE OF A KERR BH

(WITH $M = E^{\text{light-ring}}$, $J = J^{\text{light-ring}}$)

AT THE (ν-DEFORMED) LIGHT-RING

Buonanno, Damour '00



T 18/6

POSSIBLE FUTURE IMPROVEMENTS

HIGHER PERTURBATIVE ACCURACY in H and $\mathcal{F}$

CLOSE LIMIT APPROXIMATION

Smarr, Price, Pullin...

recently: Baker et al '01

NUMERICAL CALC.

BH initial data: Cook; Baumgarte, Grandclément ...

Damour, Iyer, Sathyaprakash gr-qc/0010009 1

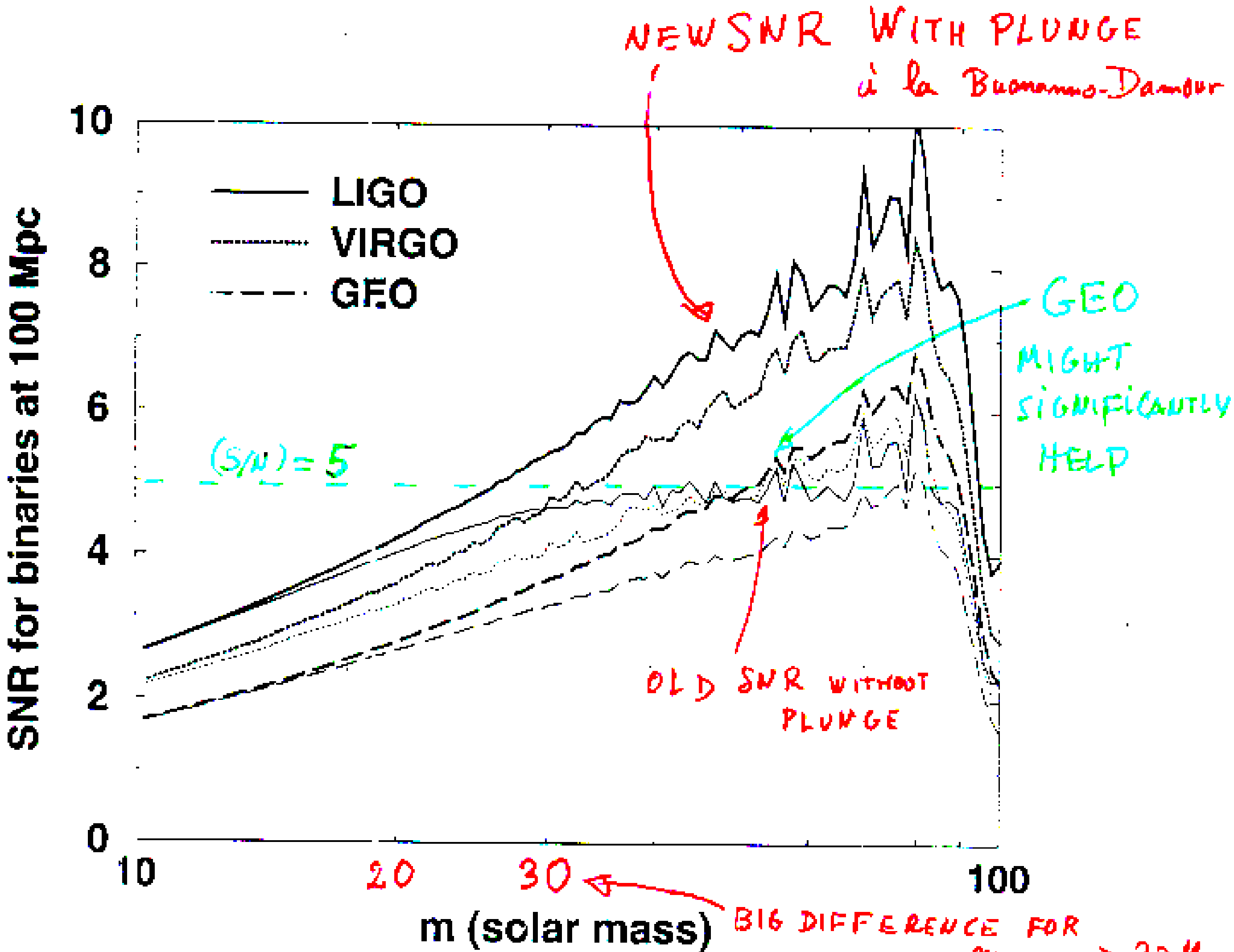


FIG. 1. Signal-to-noise ratios in GEO, LIGO-I and VIRGO when using as Fourier-domain template the post-Newtonian model Eq. (3.6) (T^{f2}), truncated at the test-mass $F_{lso} = 4400 M_\odot/m$ Hz (in thin lines), compared to the optimal one obtained when the template coincides with the fiducial "exact" (effective one-body) signal (thick lines). As usual, we averaged over all the angles. The overlaps are maximised over the time lags, the phases, and the two individual masses m_1 and m_2. The plots are jagged because we have computed the SNR numerically by first generating the fiducial "exact" waveform in the time-domain and then using its discrete Fourier transform in Eq.(5.3). The greater SNR achieved by effective one-body waveforms for higher masses, as compared to Fig 1 of DIS2, is due to the plunge phase present in these waveforms. Observe that the presence of the plunge phase in the latter significantly (up to a factor of 1.5) increases the SNR for masses $m > 35 M_\odot$. Using the effective one-body templates will, therefore, enhance the search volume of the interferometric network by a factor of 3 or 4.

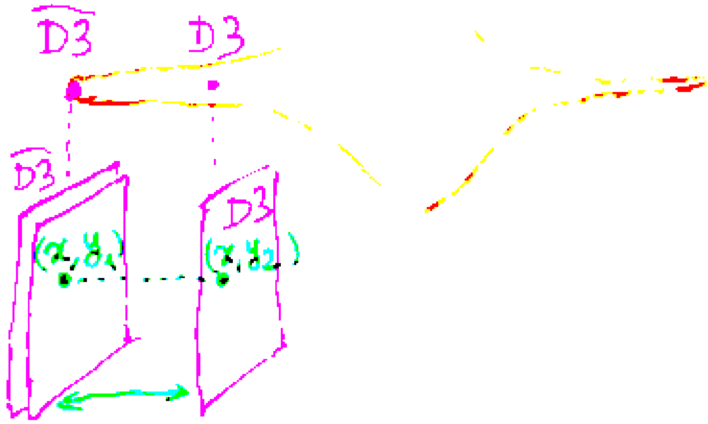
COSMIC SUPERSTRINGS (?)

Witten '85; ... Dvali, Tye; Tye, ...; KKLMMT; Copeland, Myers, Polchinski; Dvali, Vilenkin

10 dim spacetime:

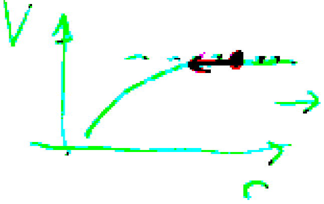
$X^M = (x^\mu, y^a)$

x^μ: 4; y^a: 6 COMPACT



$r \sim |y_1 - y_2|$

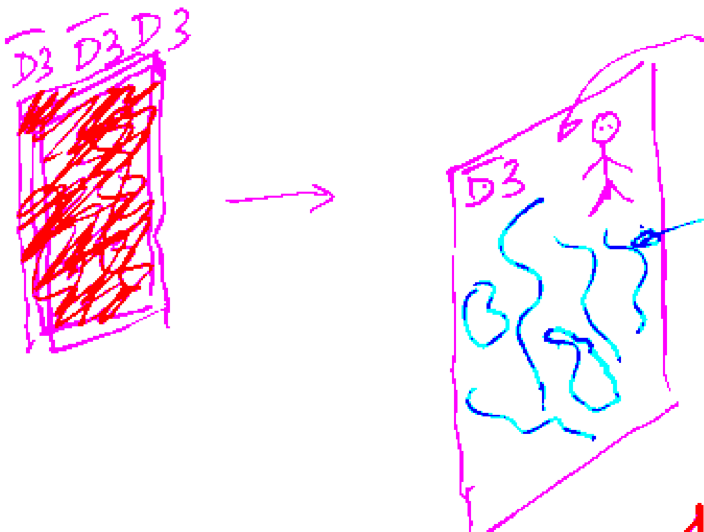
$$V(r) = A - \frac{B}{r^4}$$



SLOW ROLL INFLATION

$\varphi(x) = r(x)$

HEAT OF HOT BIG BANG



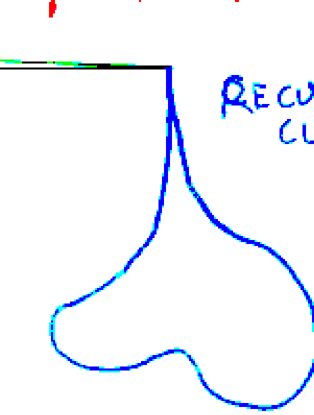
OUR WORLD

COSMOLOGICAL NETWORK OF MASSIVE (F OR D) STRINGS

WITH STRING TENSION

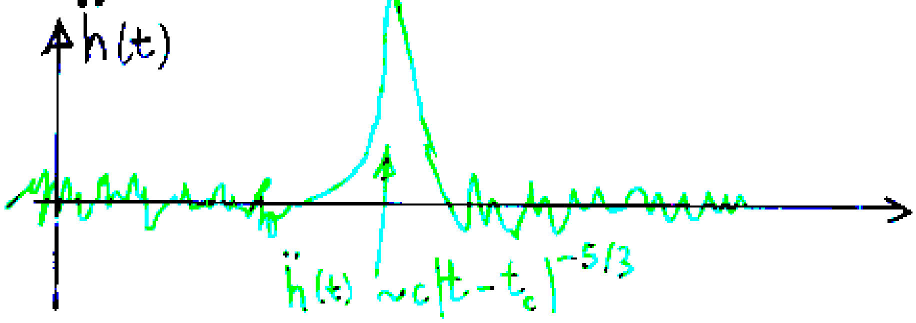
$10^{-11} \lesssim G\mu \lesssim 10^{-6}$ Tye

$G\mu \sim 10^{-8}$ - 10^{-9} KKLMMT Copeland MP



RECURRENT CUSPS

GRAVITATIONAL WAVE BURSTS



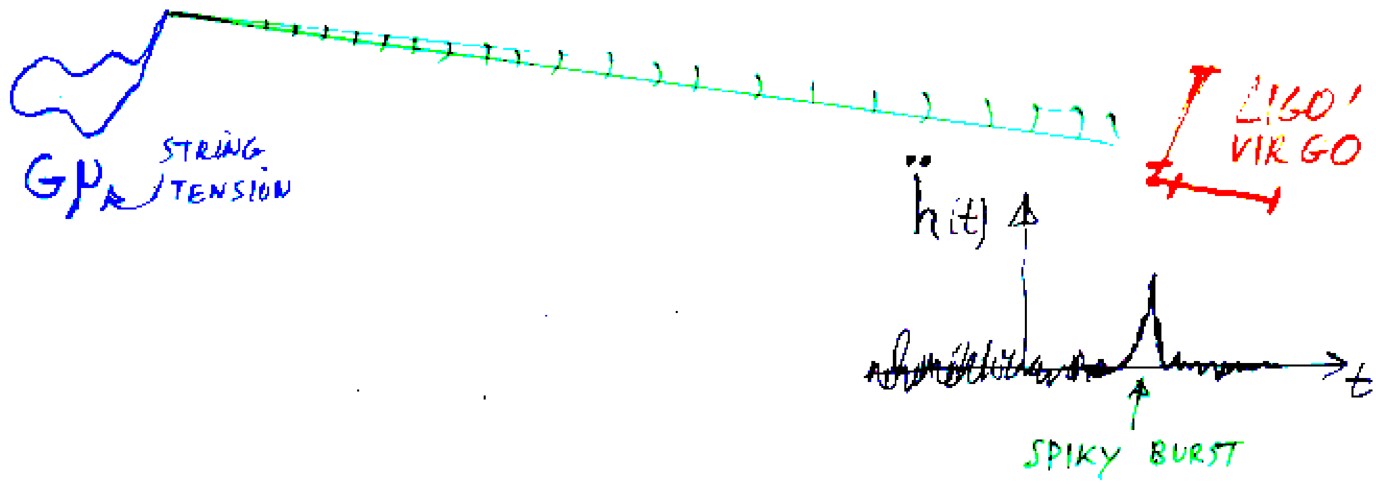
$\ddot{h}(t) \sim c|t - t_c|^{-5/3}$

POTENTIALLY DETECTABLE IN LIGO/VIRGO/...; LISA; PULSAR TIMING

Damour, Vilenkin

GRAVITATIONAL WAVE BURSTS FROM MASSIVE STRINGS

(Damour, Vilenkin '00)



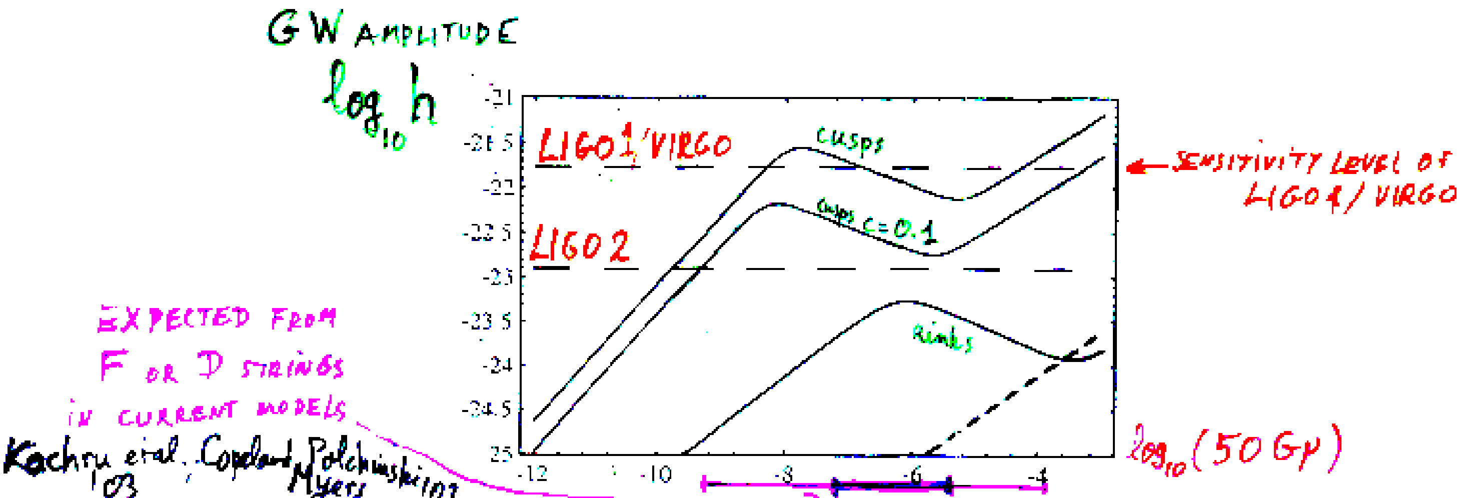


FIG. 1. Gravitational wave amplitude of bursts emitted by cosmic string cusps (upper curves) and kinks (lower curve) in the LIGO/VIRGO frequency band, as a function of the parameter $\alpha = 50\,G\mu$ (in a base-10 log-log plot). The upper curve assumes that the average number of cusps per loop oscillation 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.

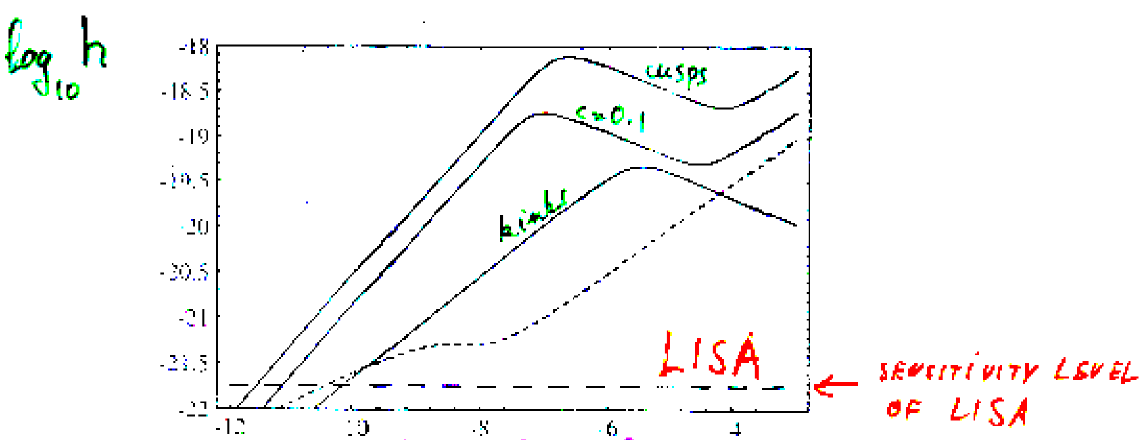
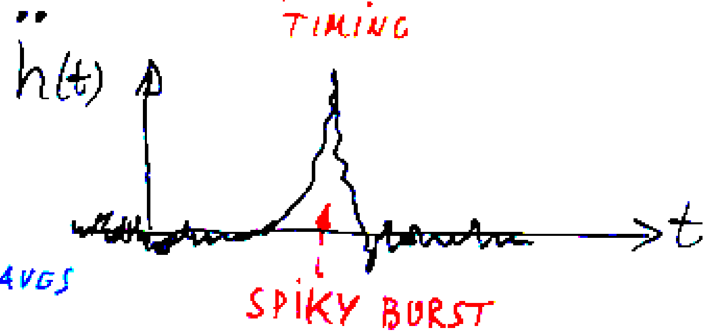


FIG. 2. Gravitational wave amplitude of bursts emitted by cosmic string cusps (upper curves) and kinks (lower curve) in the LISA frequency band, as a function of the parameter $\alpha = 50\,G\mu$ (in a base-10 log-log plot). The meaning of the three solid curves is as in Fig. 1. The short-dashed slanted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

GRAVITATIONAL WAVE BURSTS FROM COSMIC (SUPER)STRINGS

(STRONGLY) NON GAUSSIAN
STOCHASTIC BACKGROUND OF GRAV. WAVES



UNKNOWN PARAMETERS: μ, p, ϵ

- STRING TENSION μ — RECENT SCENARIOS $\rightsquigarrow$ $10^{-11} \lesssim G\mu \lesssim 10^{-6}$ (Tye et al.)
- RECONNECTION PROBABILITY $0 < p \leq 1$ — RECENT SCENARIOS $10^{-3} \lesssim p \lesssim 1$ (Polchinski et al.)
- TYPICAL LENGTH OF NEWLY FORMED LOOPS $\ell = \epsilon\, 50\, G\mu t$ — RECENT SCENARIOS $\epsilon \ll 1$ (Siemens et al.)

POSSIBILITY OF DETECTING SUCH GW BURSTS
IN LIGO 1, LIGO 2, LISA AND PTA

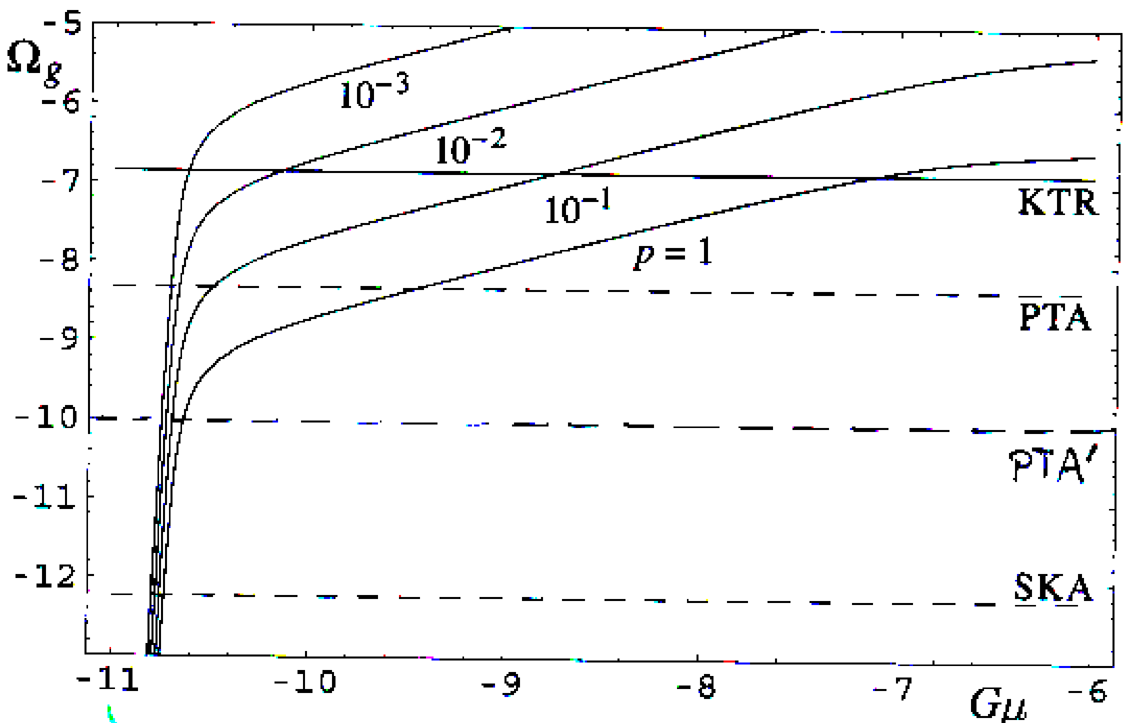
$$\boxed{\Omega_g(f)\, h^2 \sim 10^{-9.13}\, c \left(\frac{G\mu}{10^{-10}}\right)^{2/3} p^{-1} \epsilon^{-1/3} \left(\frac{f}{(10\,\mathrm{yr})^{-1}}\right)^{-\frac{1}{3}}}$$

Damour, Vilenkin '04

OF CUSPS $c \lesssim 1$

TEND TO INCREASE THE SIGNAL!

T21



?

SUGGESTED (ALLOWED) RANGE

CONCLUSION: GRAVITY: A NEW FRONTIER

- FOR A LONG TIME, GRAVITY AND GENERAL RELATIVITY WERE
  - EXPERIMENTALLY BADLY TESTED
  - ASTROPHYSICALLY NEARLY USELESS $\left(\frac{v^2}{c^2} \sim \frac{GM}{c^2 R} \lll 1 \right)$
  - COSMOLOGICALLY USEFUL, BUT POOR DATA
  - THEORETICALLY ISOLATED FROM REST OF PHYSICS

- TODAY, THE SITUATION IS QUITE DIFFERENT
  - EXPERIMENTALLY
    - HIGH-PRECISION CONFIRMATIONS
      - 10^{-5} WEAK-FIELD
      - 10^{-3} STRONG-FIELD
    - GRAV. WAVES: A NEW WINDOW ON THE UNIVERSE
  - ASTROPHYSICALLY: CRUCIALLY USEFUL: NS, BH, GW, ...
  - COSMOLOGICAL DATA: NOW HIGH-PRECISION (FEW %) → DARK ENERGY, ...
  - THEORETICALLY: GR IS CENTRAL IN STRING THEORY: $g_{\mu\nu}$ AS MASSLESS EXCITATION OF CLOSED STRINGS

    BUT "GRAVITY SECTOR" OF STRING THEORY IS POTENTIALLY MUCH RICHER THAN GR

⟹ ? BEYOND EINSTEIN'S GR ?

NEW EXPERIMENTAL OPPORTUNITIES: E.G. SHORT-RANGE DEVIATION, $\cancel{EP}$, ...

AT THE SAME TIME: HIGH-PRECISION TESTS + THEIR THEORET. INTERPRET. } ⟹ CAN TRUST GR PREDICTIONS