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LONG-DISTANCE GRAVITY AND VIOLATION OF LORENTZ INVARIANCE

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LONG DISTANCE GRAVITY
AND
VIOLATION OF LORENTZ INVARIANCE.

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- MOTIVATION.

ACCELERATED EXPANSION OF THE UNIVERSE

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \varkappa T_{\mu\nu}$$

NEW PHYSICS? (quintessence, vacuum,...)

NEW PHYSICS?

Gravity modified at cosmological length/time scale

$$l_{grav} \sim H_0^{-1} \sim 10^{28}\ \mathrm{cm}$$

AT FIRST sight, plausible in brane-world theories with large/infinite extra dimensions:

GRAVITONS LEAKING INTO EXTRA DIMENSIONS

Charmousis, Gregory, V.R. '99
Gregory, V.R., Sibiryakov '00
Kogan, Mouslopoulos, Papazoglou, Ross, Santiago '99

Dvali, Gabadadze, Porrati '00

However,

PROBLEM WITH THEORETICAL CONSISTENCY, PHENOMENOLOGICAL VIABILITY

- WHAT ARE THE PROBLEMS
- HOW LORENTZ VIOLATION MAY HELP
- OPEN ISSUES (MANY!)

BOTTOM UP APPROACH:

TRY TO MODIFY GRAVITY AT $\ell \gtrsim \ell_g$,

SEE WHAT IS THE PRICE.

PROTOTYPE MODEL: MASSIVE GRAVITY ABOUT FLAT BACKGROUND

$$\mathcal{L} = M_{Pl}^2 \left(R\sqrt{g} + m_1^2 h_{\mu\nu} h^{\mu\nu} + m_2^2 \, h_\mu^\mu h_\nu^\nu \right)$$

EXTRA DEGREES OF FREEDOM

(massive/massless TENSOR $\Leftrightarrow$ 5/2 polarisations

$$m_1 \sim m_2 \sim m_g$$

Want $m_g^{-1} = \ell_g \sim 10^{28}$ cm.

"High energy" regime: $\omega, |\vec{p}| \gg m_g$

New degrees of freedom $\Leftrightarrow$ would-be gauge modes

Stückelberg trick

Arkani-Hamed, Georgi, Schwartz '02

$$h_{\mu\nu} = \partial_\mu \pi_\nu + \partial_\nu \pi_\mu + \partial_\lambda \pi_\mu \cdot \partial^\lambda \pi_\nu + \ldots$$

π_μ does not enter Einstein-Hilbert part of action.

ENTERS ONLY THROUGH MASS TERMS.

Quadratic Lagrangian

$$\mathcal{L}_{\pi}^{(2)} = M_{Pl}^2 \left[2 m_1^2 \left(\partial_\mu \pi_\nu \partial_\mu \pi_\nu + \partial_\mu \pi_\nu \cdot \partial_\nu \pi_\mu \right) + 4 m_2^2 \left(\partial_\mu \pi^\mu \right)^2 \right]$$

- Transverse part: $\partial_\mu \pi_\mu^T = 0$

$$\Downarrow$$

$$\mathcal{L}_{\pi^T}^{(2)} = 2 M_{Pl}^2 \cdot m_1^2 \left(\partial_\mu \pi_\nu^T \right)^2$$

Kinetic term for π_μ^T.

Canonically normalised

$$\pi_\mu^T = \frac{1}{M_{Pl} \cdot m_g} \pi_\mu^{T, can}$$

<u>Interactions:</u>

$$\mathcal{L}_{int} = M_{Pl}^2 m_g^2 \left(\partial \pi^T \right)^3$$

$$= \frac{1}{M_{Pl} m_g} \left(\partial \pi^T \right)^3$$

$$\Downarrow$$

UV strong coupling scale $E_{strong} = \sqrt{M_{Pl} \cdot m_g}$

$$\Downarrow$$

$l_{stong} = \sqrt{l_{Pl} \cdot l_g} \sim 0.1\ mm$

Not too dangerous.
Even interesting

Perfect analogy to massive Yang-Mills.

- SCALAR SECTOR, $\pi^L_\mu = \partial_\mu \varphi$

$$\mathcal{L}^{(2)}_\varphi = 4 M_{Pl}^2 (m_1^2 + m_2^2)(\Box \varphi)^2$$

Higher derivative theory $\Longrightarrow$ GHOST
Negative energy, <u>unbounded from below</u>. <u>TOO BAD.</u>

FIERZ - PAULI $\quad m_2^2 = -m_1^2$

No genuine kinetic term for $\pi^L_\mu = \partial_\mu \varphi$

But mixing with $h = h^\mu_\mu$ (conformal "mode")
not PURE GAUGE.

$$\mathcal{L}^{(2)}_{h,\varphi} = M_{Pl}^2 \left[-(\partial h)^2 + m_g^2 \, h \cdot \partial^2 \varphi \right]$$

Diagonalize BY SHIFT $\quad h_{\mu\nu} \to h_{\mu\nu} + m_g^2 \eta_{\mu\nu} \varphi$

$\Downarrow$

Kinetic term for φ

$$\mathcal{L}^{eff}_\varphi = M_{Pl}^2 \cdot m_g^4 \cdot (\partial \varphi)^2$$

Canonically normalized: $\quad \varphi = \dfrac{1}{M_{Pl} \cdot m_g^2} \varphi^{can}$

$\Downarrow$

Interaction

$$M_{Pl}^2 \cdot m_g^2 (\partial\partial\varphi)^2 = \frac{1}{M_{Pl} m_g^4} (\partial\partial\varphi^{can})^3$$

STRONG COUPLING scale

$$l_{strong} = \left(l_{pl} \cdot l_g^4 \right)^{1/5} \sim 10^{14} \text{ cm}$$

AT BEST

$$l_{strong} = \left(l_{pl} \cdot l_g^2 \right)^{1/3} \sim 1000 \text{ km}$$

Arkani-Hamed, Georgi, Schwartz '0.

Explicit check:
scattering amplitudes, Aubert '03
loop effects

Cannot trust theory below $l_{strong} \sim 1000$ km.

Unacceptable

STORY REPEATS ITSELF IN EXTRA Dim's:

EITHER GHOST
OR STRONG COUPLING AT $l_{strong} \sim 1000$ km

(Except, maybe, DGP
Nicolis, Rattazzi '04).

WHAT IF LORENTZ INVARIANCE IS VIOLATED BY GRAVITON MASS TERMS?

Motivation: Einstein gravity ≈ gauge theory of Lorentz GROUP   Utiyama; Kibble

Expect Higgs phase ⟺ BROKEN LORENTZ SYMMETRY.

Assuming SYMMETRY under spatial ROTATIONS:

$$\mathcal{L}_M = M_{Pl}^2 \left[m_0^2 h_{00}^2 + 2m_1^2 h_{0i} h_{0i} - m_2^2 h_{ij} h_{ij} + m_3^2 h_{ii} h_{jj} - 2m_4^2 h_{00} h_{ii} \right]$$

NB: Fierz-Pauli: $m_0 = 0$, $m_1^2 = m_2^2 = m_3^2 = m_4^2$

- OPTION #1: $m_0 \neq 0$, $m_1 = m_2 = m_3 = m_4 = 0$

anti-FP

CLOSELY RELATED TO SCALAR FIELD LINEAR IN t
cf. Lehnert's talk
GHOST CONDENSATE
cf. Thaler's talk

Gravity modified at <u>length</u> scale $\ell_g \sim H_0^{-1}$

BUT MUCH LARGER <u>time</u> scale $t_g \gg H_0^{-1}$.

NO ACCELERATION OF THE UNIVERSE.

OPTION # 2: V.R. '04

$$m_0 = 0$$

a la' Fierz-Pauli:

$$m_1, m_2, m_3, m_4 \neq 0, \sim m_g$$

Again study would-be pure gauge modes

$$h_{\mu\nu} = \partial_\mu \pi_\nu + \partial_\nu \pi_\mu + \partial_\lambda \pi_\mu \cdot \partial_\lambda \pi_\nu + \dots$$

Quadratic Lagrangian

$$\mathcal{L}_\pi^{(2)} = M_{Pl}^2 \cdot m_g^2 \, [c_1 \, \partial_0 \pi_0 \cdot \partial_i \pi_i + c_2 (\partial_i \pi_0)^2 + c_3 (\partial_0 \pi_i)^2 - c_4 (\partial_i \pi_j)^2 - c_5 (\partial_i \pi_i)^2]$$

c_i = combinations of m_i / m_g

- π_0 not dynamical, Lagrange multiplier

(for $m_0 \neq 0$ it is generically a ghost)

- HEALTHY kinetic terms FOR π_i^T $(\partial_i \pi_i^T = 0)$ **AND** $\pi_i^L = \partial_i \varphi$

$$\mathcal{L}_{\pi^T, \pi^L} = M_{Pl}^2 m_g^2 \, [\mathbb{C}_1^{T,L} (\partial_0 \pi^{T,L})^2 - \mathbb{C}_2^{T,L} (\partial_i \pi_j^{T,L})^2]$$

$\mathbb{C}$'s = combinations of m_i / m_g.

$\mathbb{C}_{1,2}^L$ both vanish in Fierz-Pauli limit $m_1 = \dots = m_4$.

SINGLE STRONG COUPLING SCALE

$$l_{strong} = \sqrt{l_{Pl} \cdot l_g} \sim 0.1 \text{ mm}.$$

Dispersion relations

- Tensor modes: Transverse traceless h_{ij}

$$\omega^2 = \vec{p}^{\,2} + m_2^2$$

- Vector modes: $h_{ij} = \partial_i \pi_j^T + \partial_j \pi_i^T$

$$\omega^2 = \frac{m_2^2}{m_1^2}\vec{p}^{\,2} + m_2^2$$

- Scalar mode: $h_{ij} = \partial_i \partial_j \varphi + \dots$

$$\omega^2 = \frac{\vec{p}^{\,2} + \mu_1^2}{\vec{p}^{\,2} + \mu_0^2} \cdot c^2 \vec{p}^{\,2} + m_2^2 \frac{\mu_0^2}{\vec{p}^{\,2} + \mu_0^2}$$

$\mu_0, \mu_1 \sim m_g$; $c \sim 1$ = combinations of masses.

* All have gap:

$$\omega^2(\vec{p}=0) = m_2^2$$

* Lorentz violation in vector and scalar sectors, not tensor

NB: smooth limit $m_g \to 0$, unlike van Dam - Veltman - Zakharov in Fierz-Pauli case.

Sensible massive gravity down to 0.1 mm.

OTHER OPTIONS WITHOUT GHOSTS, TACHYONS:

Dubovsky '04

$$m_0^2 \neq 0 \begin{array}{l} \nearrow \\ \searrow \end{array} \begin{array}{c} m_2^2 = m_3^2 \\ \text{OR} \\ m_1^2 = 0 \end{array}$$

PROTECTED BY UNBROKEN PART OF DIFFEOMORPHISM INVARIANCE.

Tensor modes still massive; smooth limit $m_g \to 0$.

Speculation:

- Accelerating Universe may mean that Lorentz invariance is violated in gravitational sector

- New (quantum?) gravity physics at and below $l_{strong} \sim 0.1$ mm

A lot has to be understood before this becomes better grounded

- Mechanism(s) to generate Lorentz violating graviton masses

  Vector field condensate?

  - Stability against higher order terms [Danger: ghost]
  - Hidden Boulware-Deser mode?

- Cosmology

  potentially interesting, but $m_g \neq 0$ does not necessarily mean acceleration

- Other signatures?

  A lá Moon precession

  Dvali, Gruzinov, Zaldarriaga '02

  Lue, Starkman '02

What happens below 0.1 mm?

Table-top experiments.