CHASING ZERO

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Is Graviton Mass $\neq 0$?

Signals of new gravitational physics may come from far infrared

1. Dark energy or IR-modified gravity?

2. Cosmological term. (G.D. Gabadadze Shifman; Adams, Greene, Silverstein; Arkani-Hamed et al)

Is infrared modification of GR possible? And, what is the scale r_c ?

Class of theories involved:

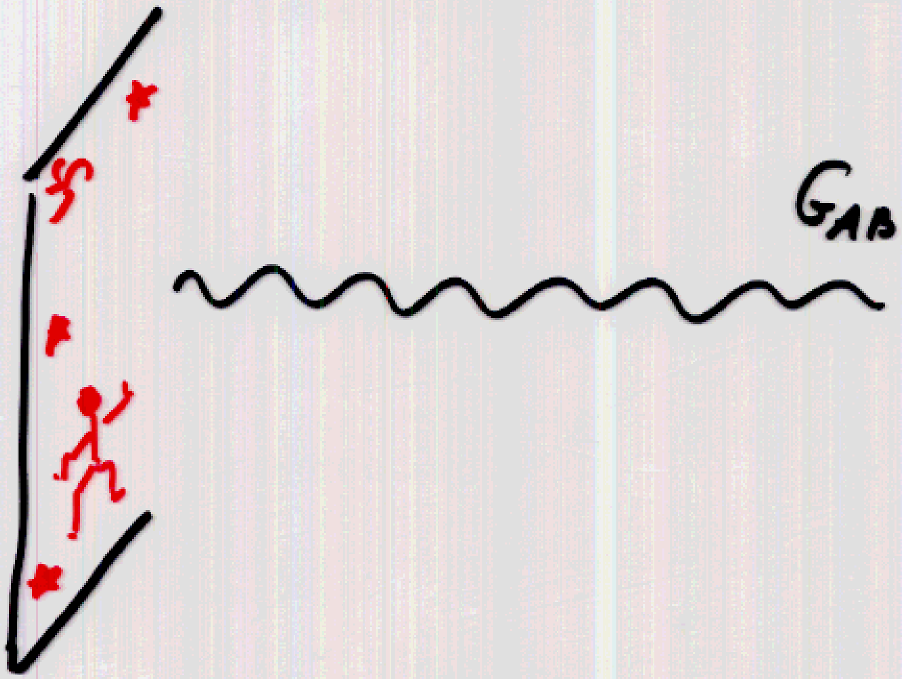
graviton propagator.

$$G(p) = \int ds \frac{\rho(s)}{p^2 - s}$$

A generally-covariant theory of far IR-modified gravity

D.-Gabadadze-Porrati

$$S = M_{pl}^2 \int d^4x \sqrt{-g}\, R_{(4)} + \frac{M_{pl}^2}{r_c} \int d^5x \sqrt{-G}\, R_{(5)}$$



Effective 4D theory:

$$M_{pl}^2\left(\Box + \frac{\sqrt{\Box}}{r_c}\right)h_{\mu\nu} = T_{\mu\nu} - \frac{1}{3}\eta_{\mu\nu}T_\alpha^\alpha$$

compare to massive gravity

$$M_{pl}^2\left(\Box + \underline{\underline{m_g^2}}\right)h_{\mu\nu} = T_{\mu\nu} - \underline{\underline{\frac{1}{3}}}\eta_{\mu\nu}T_\alpha^\alpha$$

graviton "mass" $\quad m_g^2 \rightarrow \frac{\sqrt{\Box}}{r_c}$

Newtonian gravity for $r \gg r_c$:

$$V(r) \propto \frac{1}{r^2}$$

as opposed to:

$$V(r) \propto \frac{e^{-m_g r}}{r}$$

4D picture:

FRW Equetion is modified in far infrared!

$$H^2 - \frac{H}{r_c} = \frac{8\pi}{3} G_N \rho$$

Early cosmology is normal $H \gg r_c^{-1}$

Late cosmology: $\rho \to 0$

$$H \longrightarrow H = r_c^{-1} = \text{constant}!$$

At late times Universe is self-accelerating!

No need in dark energy.

De Ffayet, D., Gabadadze

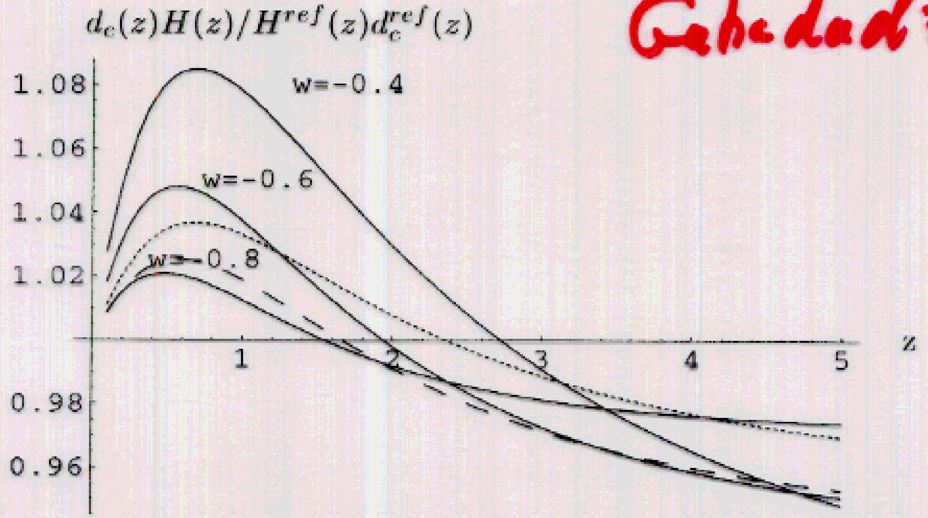


Figure 2: Plot of $H(z)d_c(z)/H^{ref}(z)d_c^{ref}(z)$ (Alcock-Paczynski test) for various models of dark energy with constant equation of state parameters w in standard cosmology (solid lines) as compared with the outcome of the model consider in this paper (dashed lines). The plot all correspond to flat universes with $\Omega_M = .3$ (solid lines, and dotted line), and $\Omega_M = .28$ (dotted line).

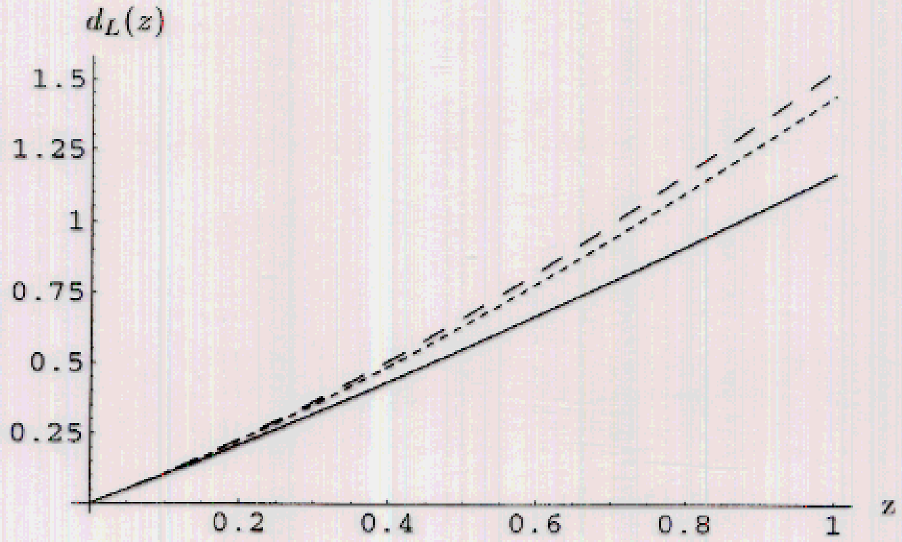
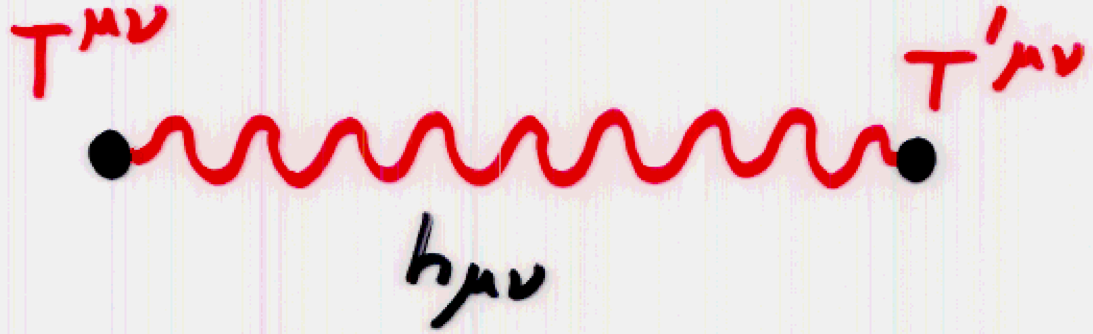


Figure 3: Luminosity distance as a function of redshift for ordinary cosmology with $\Omega_\Lambda = .7, \Omega_M = .3, k = 0$ (Dashed line), $\Omega_\Lambda = 0, \Omega_M = 1, k = 0$ (solid line), and in our model (dotted line) with $\Omega_M = .3$ and a flat universe (for which one gets from equation (15) $\omega = .12$).

One-graviton exchange



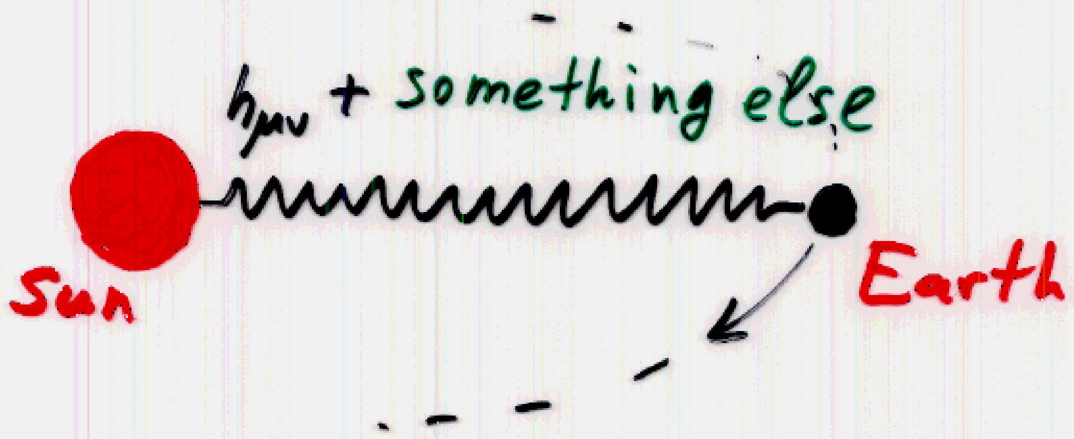
(I) Our case:

$$A \sim \frac{T'_{\mu\nu} T^{\mu\nu} - \frac{1}{3} T'^{\mu}_{\mu} T^{\nu}_{\nu}}{p^2 + p/r_c}$$

(II) case of Einstein graviton:

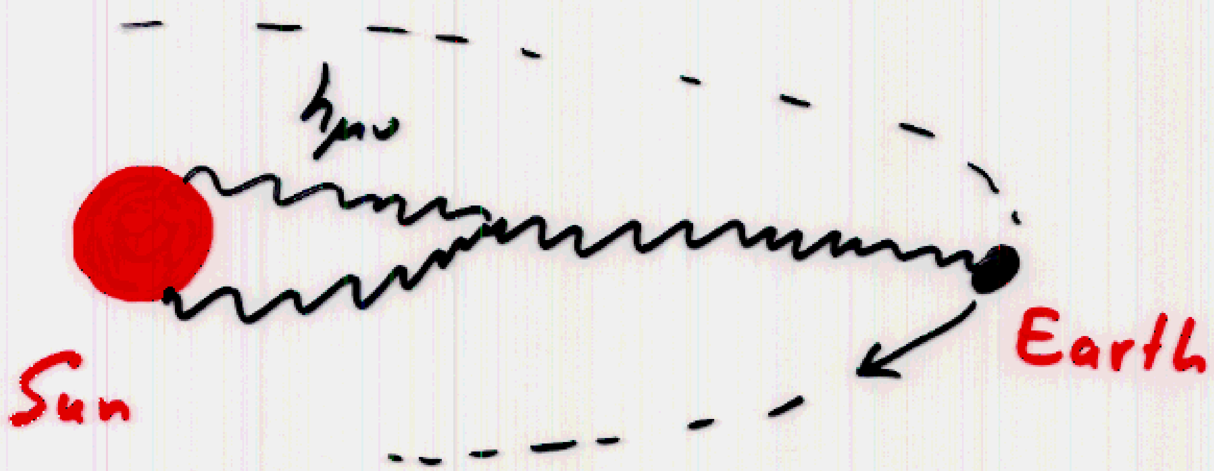
$$A \sim \frac{T'_{\mu\nu} T^{\mu\nu} - \frac{1}{2} T'^{\mu}_{\mu} T^{\nu}_{\nu}}{p^2}$$

Difference in tensor structure indicates that our graviton has extra polarizations:



Is this model ruled out?

However:



CAN GRAVITON BE MASSIVE ?

van Dam - Veltman - Zakharov Discontinuity

Graviton propagator:

Massless :

$$\Delta^{0}_{\mu\nu,\alpha\beta} = \frac{\frac{1}{2}\left(\eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\mu\beta}\eta_{\nu\alpha}\right) - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}}{p^2 - i\epsilon}$$

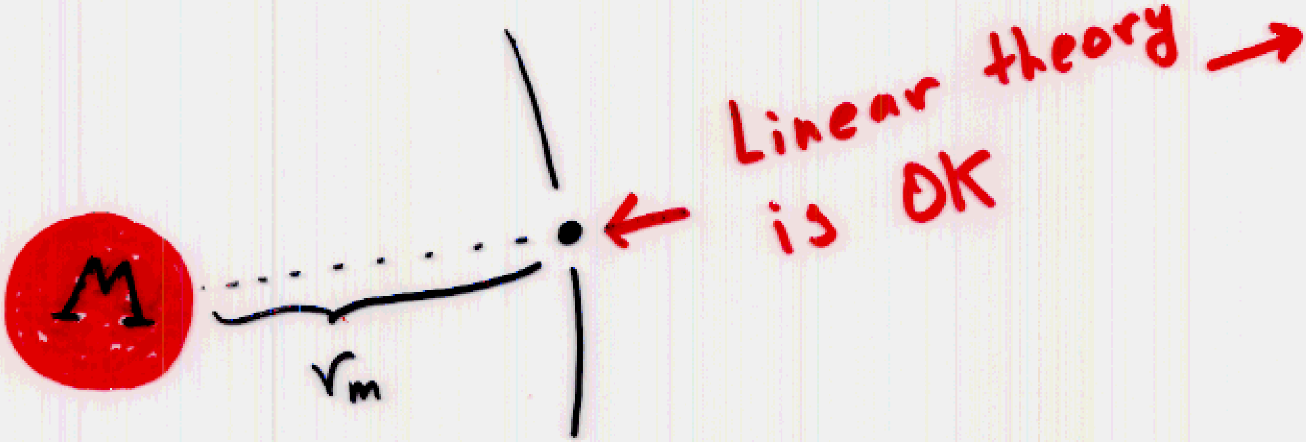
Massive:

$$\Delta^{m}_{\mu\nu,\alpha\beta} = \frac{\frac{1}{2}\left(\tilde{\eta}_{\mu\alpha}\tilde{\eta}_{\nu\beta}+\tilde{\eta}_{\mu\beta}\tilde{\eta}_{\nu\alpha}\right) - \frac{1}{3}\tilde{\eta}_{\mu\nu}\tilde{\eta}_{\alpha\beta}}{p^2 + m_g^2 - i\epsilon}$$

$$\tilde{\eta}_{\mu\nu} = \eta_{\mu\nu} + \frac{p_\mu p_\nu}{m_g^2}$$

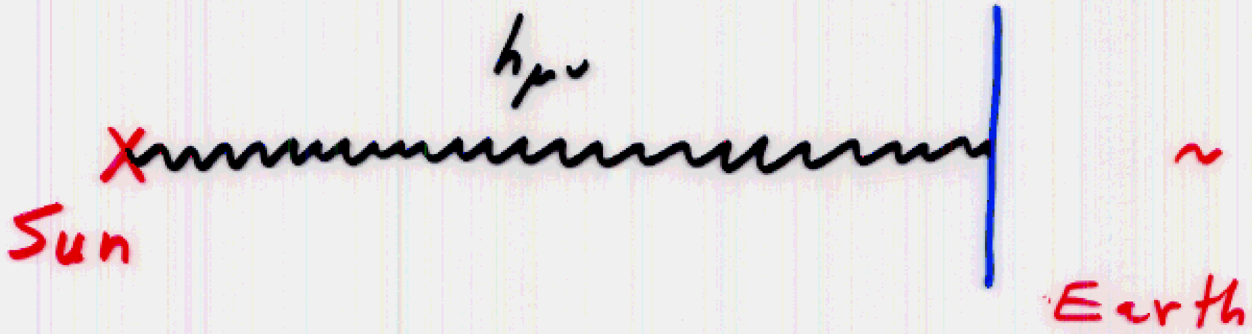
v DVZ - Discontinuity is artifact of the linear approximation which is valid only at distances

$$r \gg r_m = \frac{(m_g r_g)^{\frac{1}{5}}}{m_g} \qquad r_g \equiv 2 G_N M$$

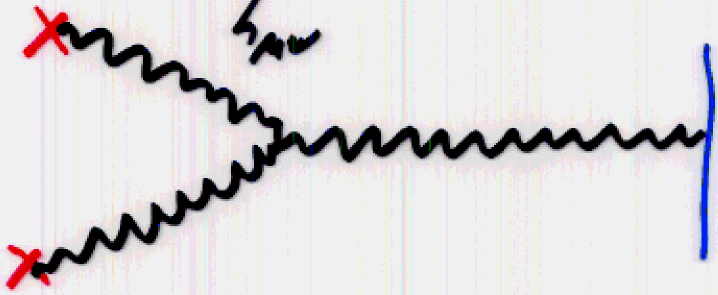


For Sun, r_m > Solar system size !

Vainshtein '72



$\sim G_N$



$\sim G_N^{\,2}$

For $r > (m_g r_g)^{\frac{1}{5}}/m_g$ G_N-expansion breaks down!

Moreover: Longitudinal polarizations of graviton become strongly coupled above:

$$p_c \sim (m_g^4 M_{pl})^{\frac{1}{5}} \longleftrightarrow \frac{p_\mu p_\nu}{m_g^2}$$

In our case: $m_g^2 \to p/r_c$

$$p_c \sim (M_{pl} r_c^{-2})^{\frac{1}{3}}$$

Deffayet, G.D., Gabadadze, Vainshtein '01

Arkani-Hamed et. al (Goldstones)

Luty et al

Absence of vDVZD in non-linear general-covariant theory:

$$S = M_{pl}^2 \left\{ \int d^4x \sqrt{-g}\, R_{(4)} + \frac{1}{r_c} \int d^5x \sqrt{-G}\, R_{(5)} \right\}$$

I. Cosmology; Deffayet, G.D., Gabadadze, Vainshtein

II. Cosmic strings; Lue

III. Schwarzschild.

Gruzinov; Porrati

We have to expand in $\frac{1}{r_c}$ not in G_N!

Perturbative in $1/r_c$ Schwarzschild solution:

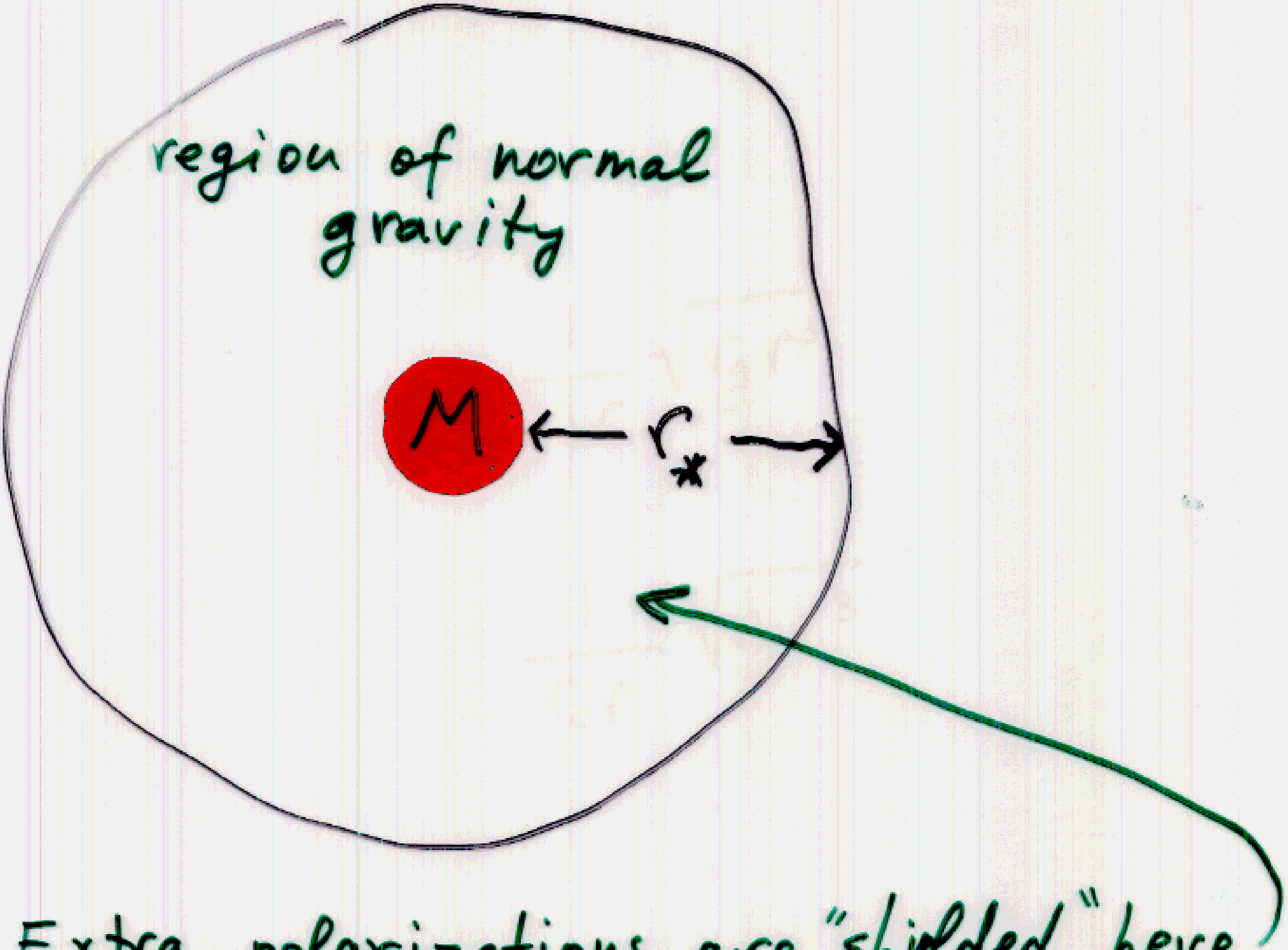
A. Gruzinov

$$\nu(r) = -\frac{r_g}{r} + \frac{1}{r_c r}\sqrt{r_g r^3}$$

$$\lambda(r) = \frac{r_g}{r} + \frac{1}{r_c r}\sqrt{r_g r^3}$$

reproduces Vainshtein's result up to:

$$m_g^2 \rightarrow \frac{1}{r r_c}$$



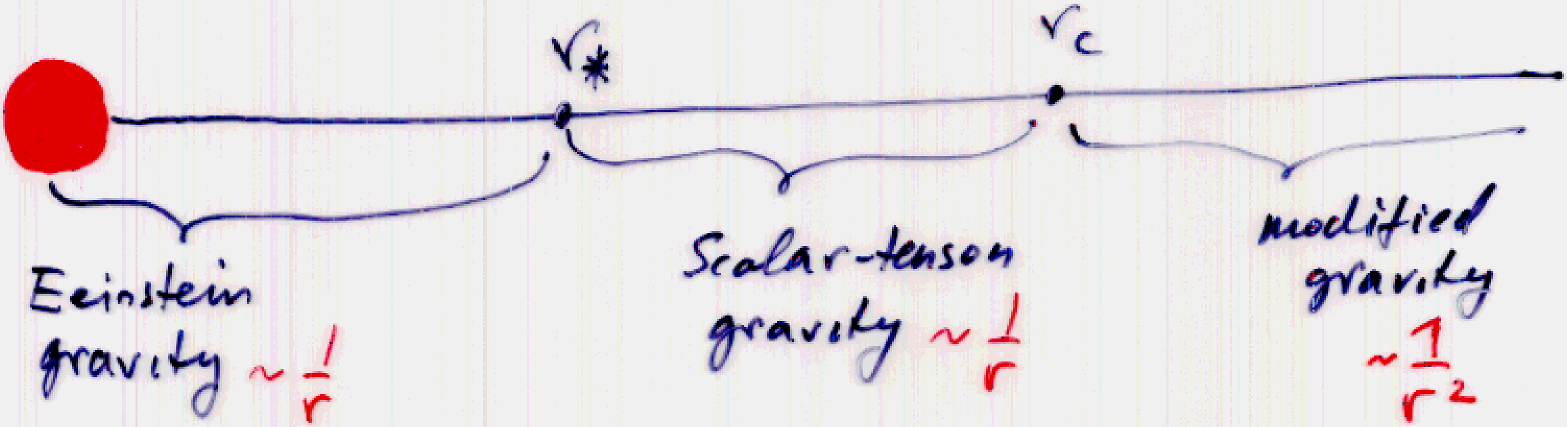
Extra polarizations are "shielded" here

$$r_* \sim \left(r_c^2 r_g\right)^{\frac{1}{3}} \ll r_c \; !$$

$$r_g \equiv 2 G_N M$$

Corrections to Schwarzschild penetrate to distances $\ll r_c$!

$$r_g \ll r_* \ll r_c$$



Fractional corrections to gravitational potential:

$$\epsilon \equiv \frac{\delta \nu}{\nu} = -\sqrt{2}\,\frac{r}{r_c}\sqrt{\frac{r}{r_g}}$$

$$r_* \sim \left(r_c^2 r_g\right)^{\frac{1}{3}} \ll r_c \;!$$

Lunar Rangin Test

G.D., A.Gruzinov, M.Zaldarriaga

Predicted anomalous perihelion precession:

$$\delta\phi = \left(\frac{3\pi}{4}\right)\frac{r}{r_c}\sqrt{\frac{r}{r_g}}$$

For Earth-Moon system:

$$\delta\phi = 1.4 \times 10^{-12}$$

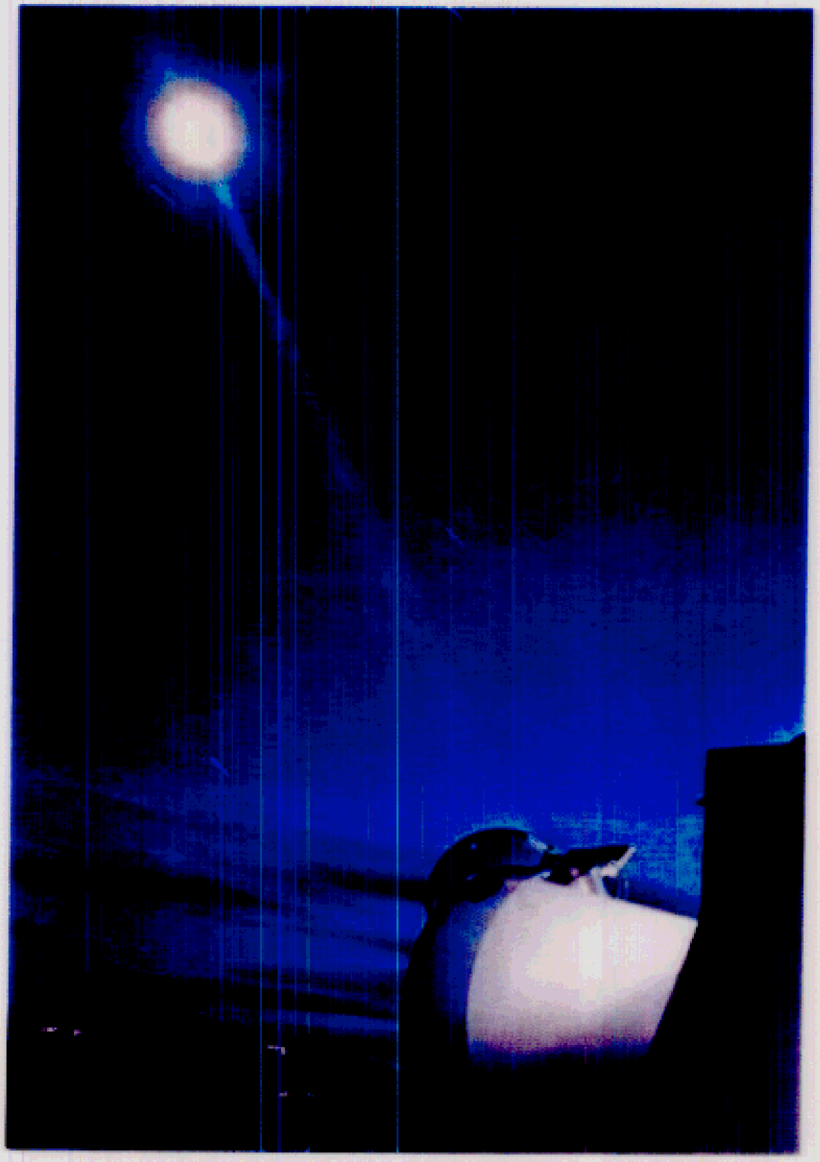
Today's accuracy:

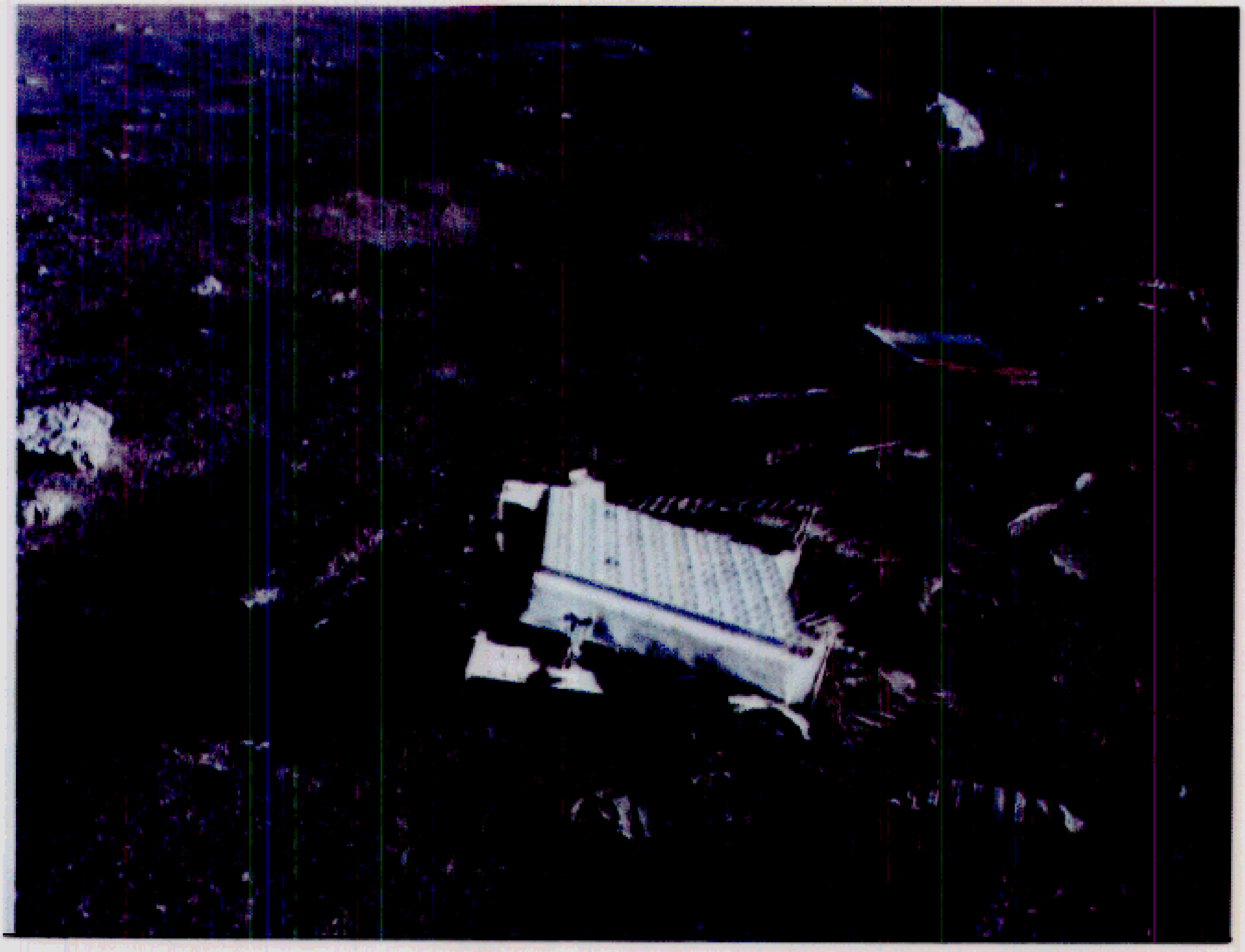
$$\sigma_\phi = 2.4 \times 10^{-11}$$

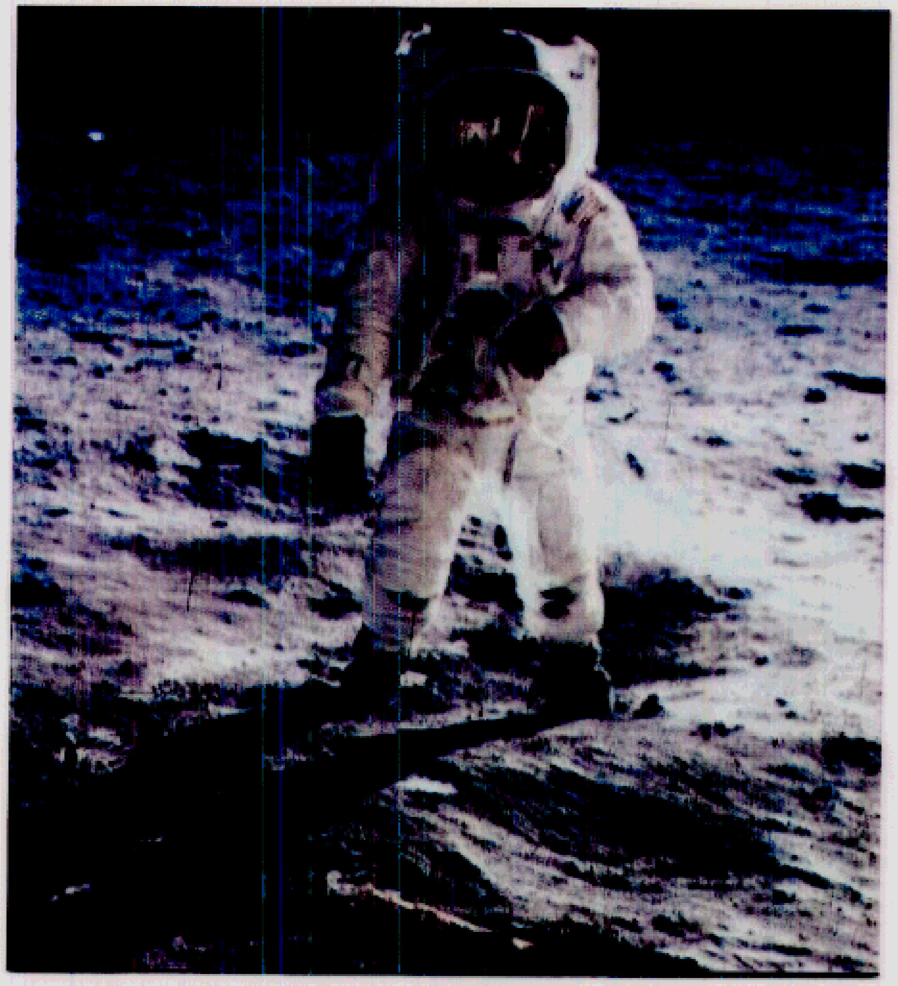
10-fold improvement is expected:

Adelberger et al

Martial ranging: Lue, Starkman







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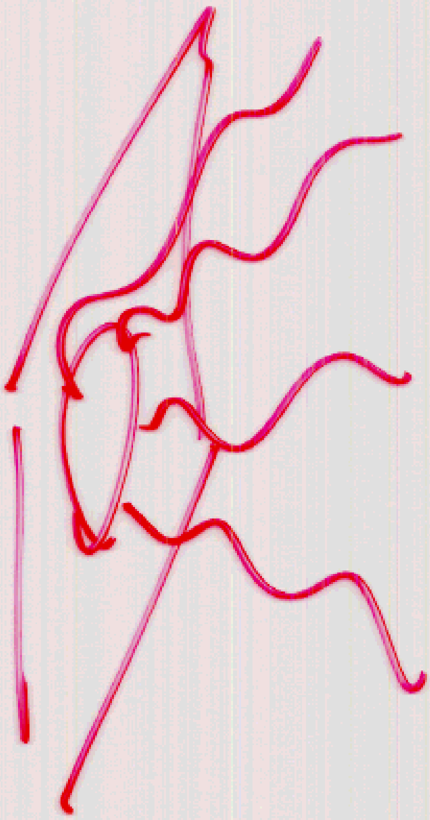
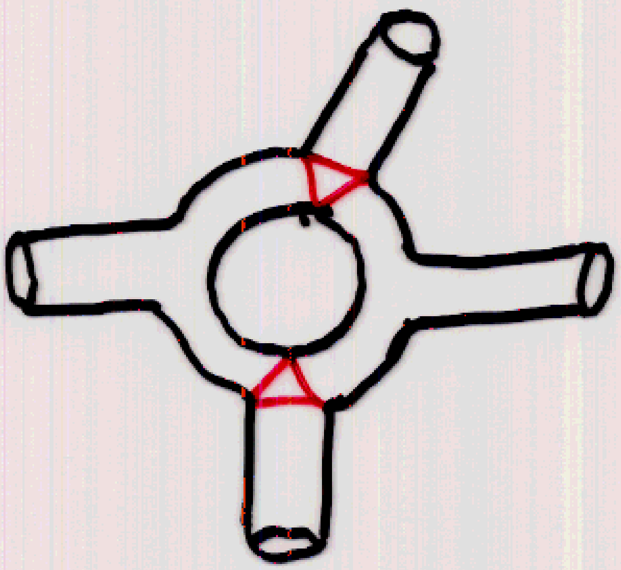
$\frac{1}{r_c}$ - resummation in loops may require string theory UV-completion

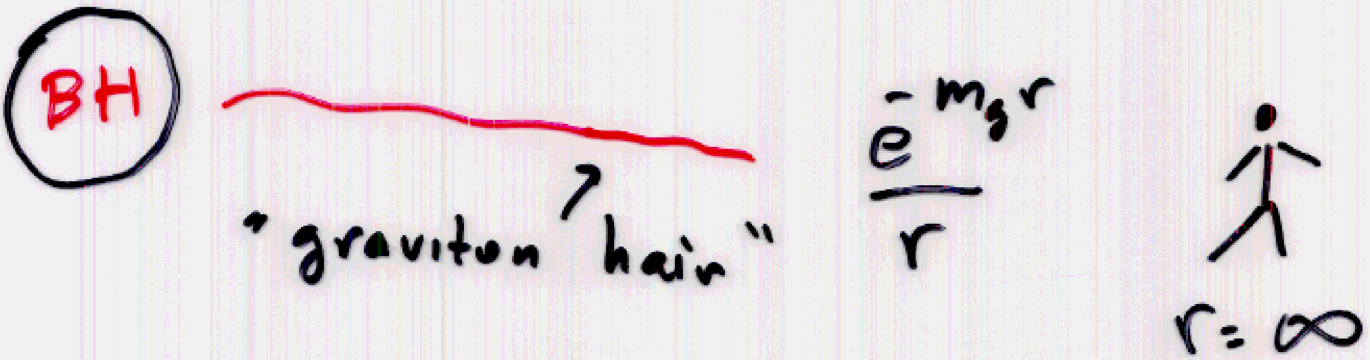




Some open issues:

Black Holes in massive and IR-[redacted] modified gravity

What about "no-hair" theorem?



BH in the flat space with $m_g \neq 0$ probably should be unstable classically

Or perhaps with $m_g \neq 0$ flat space is not a solution?

No such "paradox" in power-law-modified gravity