Fundamental Physics & Gravity at Largest Observable Distances

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Outline:

* Motivation
* Perturbative (vDVZ) discontinuity
* "Strong coupling" phenomenon
* Non-perturbative continuity
* Observational consequences:
  1. Cosmology
  2. Planetary motion
  3. LHC
  4. ......

In contrast with the dark energy models, the modified gravity theories are extremely constrained, and imply new dynamics, which is testable by:

- Precision cosmology;

- Precision gravitational measurements at all distances. E.g. Planetary motion

Motivation

* Cosmological constant problem;
* Dark energy in the Universe;
* Fundamental question:
  Can GR be modified at large distances?
* If "yes", what are the experimental consequences?

Class of theories:

1. General covariance;
2. <u>No ghosts</u>;
3. Spectral representation on Lorentz-preserving background

$$G(p) = \int_0^\infty \frac{ds\, \rho(s)}{p^2 - s}$$

$$\rho(s) \geq 0$$

The only ghost-free theory of a linearized massive gravity

$$m_g^2\left(h_{\mu\nu}h^{\mu\nu} - (h^{\alpha}_{\alpha})^2\right)$$

One graviton exchange amplitude:

$$\rightarrow \quad A(p) \propto \frac{T_{\mu\nu}T'^{\mu\nu} - \frac{1}{3}T^{\alpha}_{\alpha}T' \ldots}{p^2 + m_g^2}$$

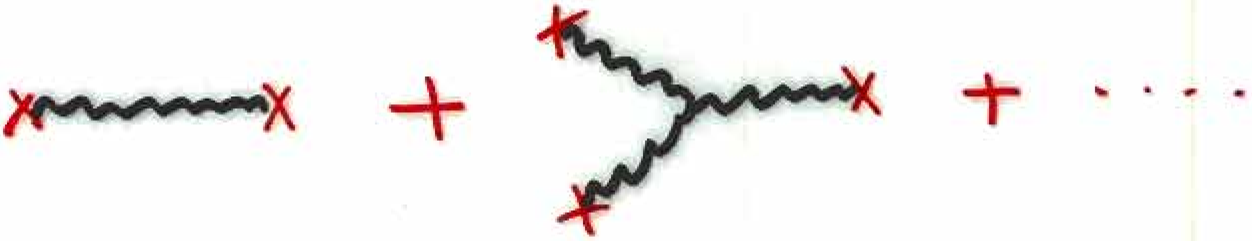
$$\Downarrow$$

For any modified gravity theory:

$$A(p) \propto \int \frac{ds\,\rho(s)}{p^2 - s}\left[T_{\mu\nu}T'^{\mu\nu} - \left(\frac{1}{2} + \alpha\right)T^{\alpha}_{\alpha}T' \ldots\right.$$

$$\alpha \geqslant \frac{1}{6}$$

So any modified gravity theory from the above class is ruled out unless the expansion in G_N breaks down at the Solar system distances



$$G_N + G_N^2 + \cdots$$

This is exactly what happense in massive gravity

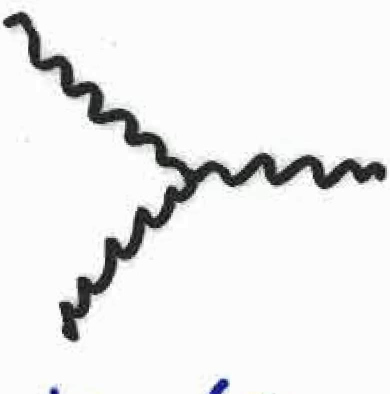
"Strong coupling" effect in massive gravity

Deffayet, G.D., Gabadadze, Vainshtein (2001)

Graviton propagator:

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

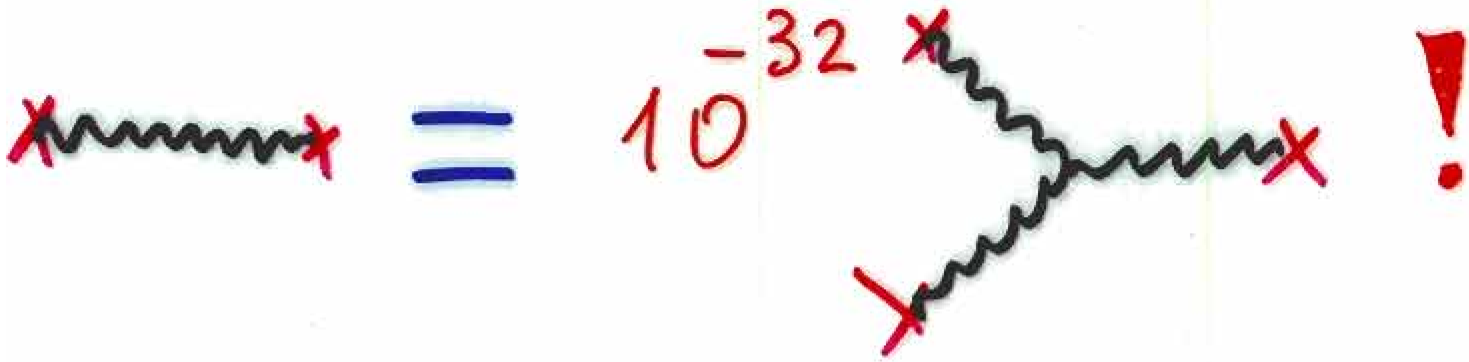
$$\tilde{\eta}_{\mu\nu} = \eta_{\mu\nu} + \frac{p_\mu p_\nu}{m_g^2}$$



$$\rightarrow \frac{p^5}{m_g^4 M_{pl}}$$

Extra (longitudinal) polarizations become strongly coupled!

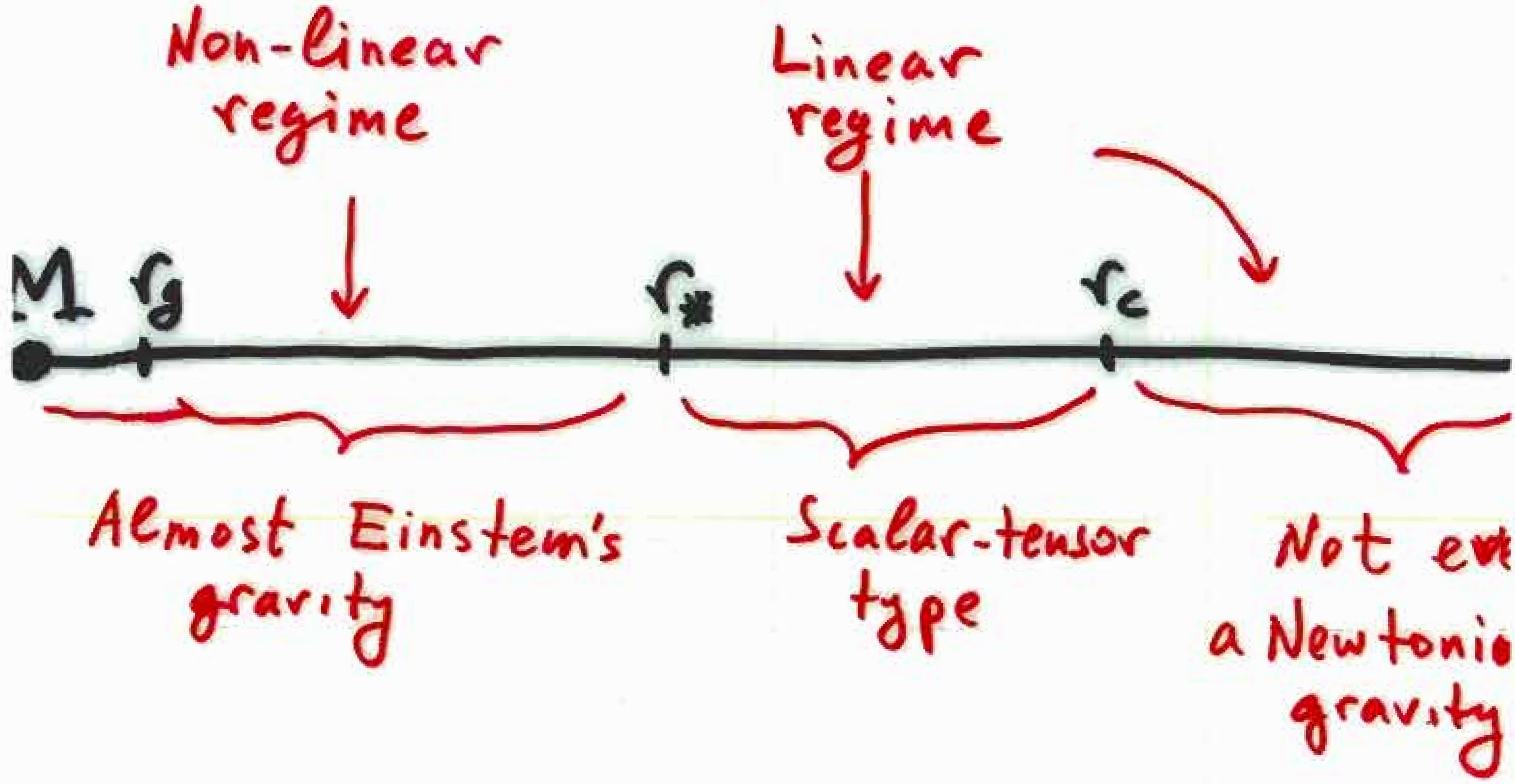
Because of the strong coupling in the solar system



G_N is not a good expansion parameter.

So is modified gravity compatible with observations?

"Now we are ready to formulate general properties of <u>any</u> large distance modified gravity theory:



$$r_c \sim H_0^{-1} \sim 10^{28}\,\mathrm{cm}$$

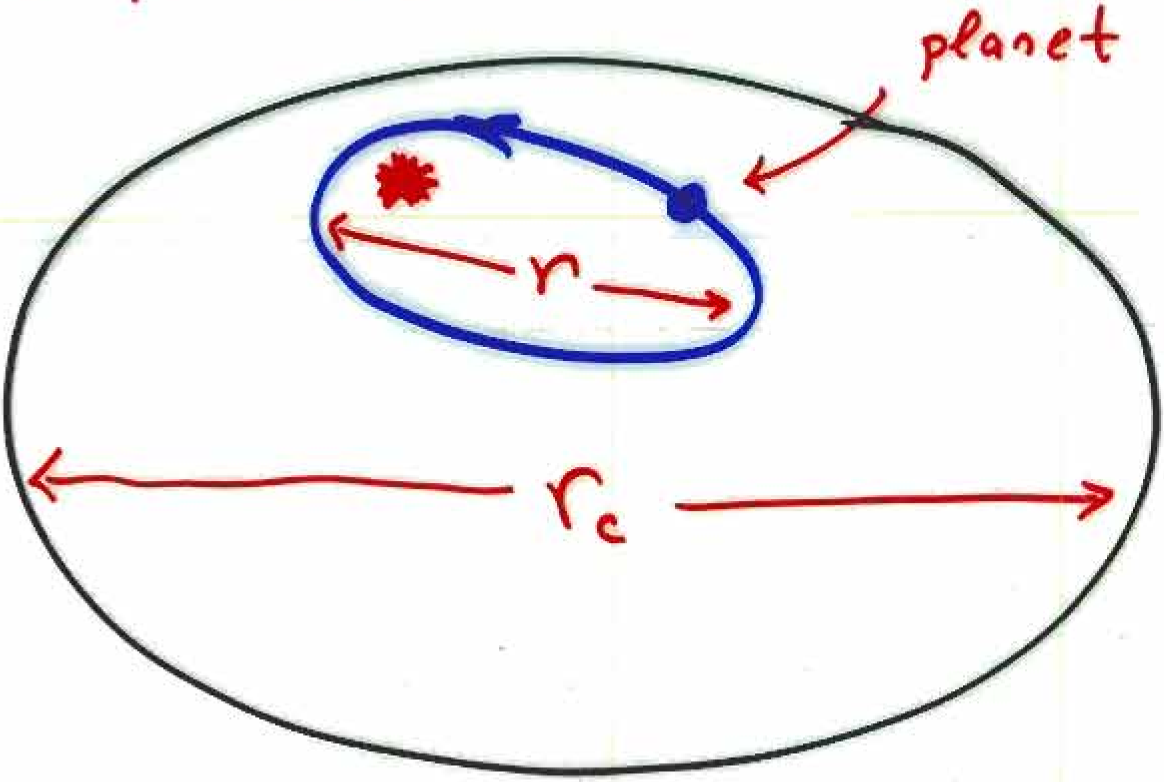
$$r_* = \left(r_c^{\alpha}\, r_g^{\beta}\right)^{\frac{1}{\alpha+\beta}}$$

for $r < r_*$ correction to the gravitational potential:

$$\frac{\delta\varphi}{\varphi} = \left(\frac{r}{r_*}\right)^{p} = \left(\frac{r}{r_c}\right)^{k} \left(\frac{r}{r_g}\right)^{q}$$

Starobinsky told me that a similar question can be asked in GR if we take $r_c = H_0^{-1} = 10^{28}$ cm,

E.g. when the expansion rate of the Universe can affect an orbit of a planet?



$$\frac{\delta\psi}{\psi} = \left(\frac{r}{r_c}\right)^p$$

We see that there is a qualitative difference:

In modified gravity:

$$\frac{\delta\psi}{\psi} = \left(\frac{r}{r_c}\right)^p \left(\frac{r}{r_g}\right)^q \leftarrow \text{Enhancement fator !}$$

In GR:

$$\frac{\delta\psi}{\psi} = \left(\frac{r}{r_c}\right)^p$$

This is because in GR there is no strong coupliy effect!

(As said above, in GR graviton has two weakly coupled polarization

DISCONTINUITY

$$S = \int d^4x \sqrt{-g} R + \frac{1}{r_c} \begin{bmatrix} \text{MODIFICATION} \\ \text{AT } r \gg r_c \end{bmatrix}$$

say, $r_c \sim H_0^{-1} \sim 10^{28}$ cm

$$\lim_{r_c \to \infty} \text{NEW GRAVITY} \neq \text{Einstein}$$

GRAVITY IS NO LONGER MEDIATED BY A MASSLESS SPIN-2 GRAVITON:

$$h_{\mu\nu}^{NEW} = h_{\mu\nu}^{EINSTEIN} + ?$$

Universe's acceleration

$$H \equiv \left(\frac{\dot{a}}{a}\right) \longrightarrow \text{const}$$

Friedmann equation (flat Universe)

$$H^2 + \ldots = \frac{8\pi}{3} G_N \rho_{Matter} + \ldots$$

Dark energy or Modified Gravity?

Connection between modified gravity and Universe's acceleration

Universe with cosmological constant:

$$\frac{8\pi}{3} G_N \rho = \Lambda = \text{constant}$$

Friedmann equation

$$H^2 = \Lambda = \text{constant}$$

$$\langle R \rangle = 12 H^2 = \text{constant}$$

CONSTANT CURVATURE ≡ GRAVITON "CONDESATE"

Massless bosons do not condense, without a source.

MASSLESS BOSONS DO NOT CONDENSE

$$\Box \Phi = 0$$

ONLY THE WAVES

$$\Phi = e^{\pm ikx}$$

BUT THE MASSIVE BOSONS DO CONDENSE!

$$(\Box + m^2)\Phi = 0$$

CONDENSATE:

$$\phi = \cos(mt)$$

In modified gravity

G.D., Turner

$$H^2 - \frac{1}{r_c^{\alpha}} H^{2-\alpha} + \ldots = \frac{8\pi}{3} G_N \rho$$

$$H = \frac{1}{r_c} = \text{const}$$

Does not require a source.

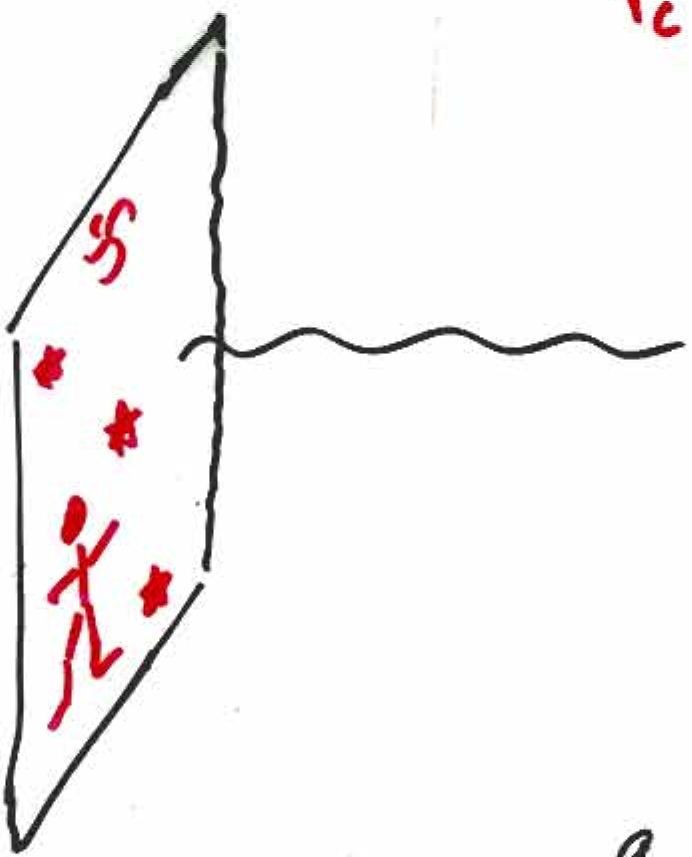
Graviton is <u>not</u> a <u>massless</u> spin-2 particle, and <u>can</u> condence, without any "dark energy" source.

$$\langle R \rangle \neq 0$$

A generally-covariant theory of IR-modified gravity

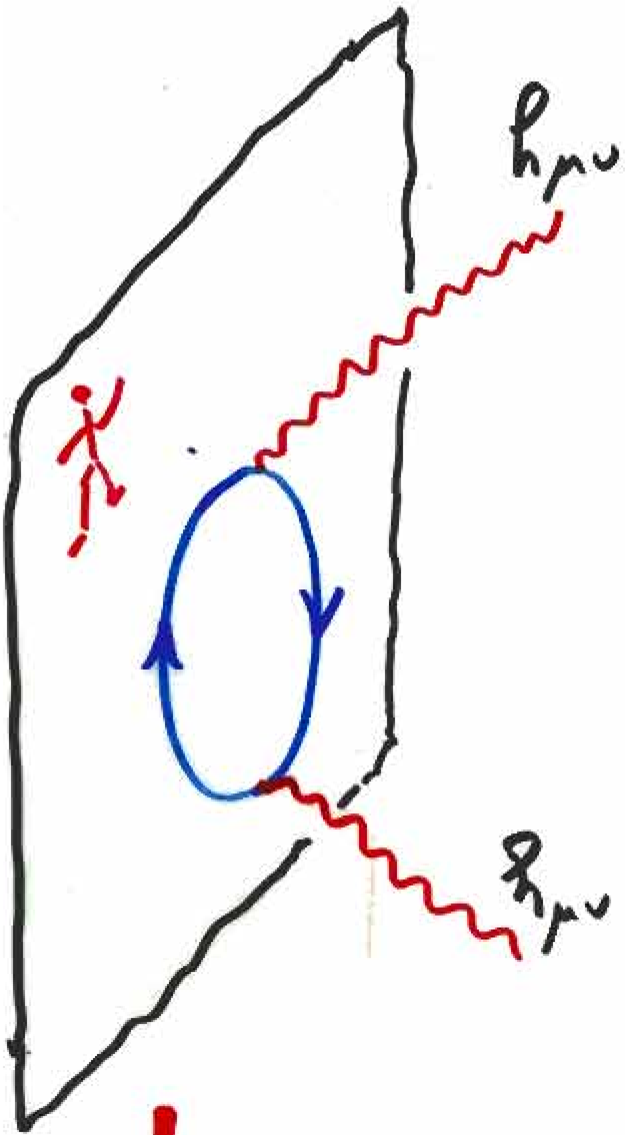
D.-Gabadadze-Porrati

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



G_{AB}

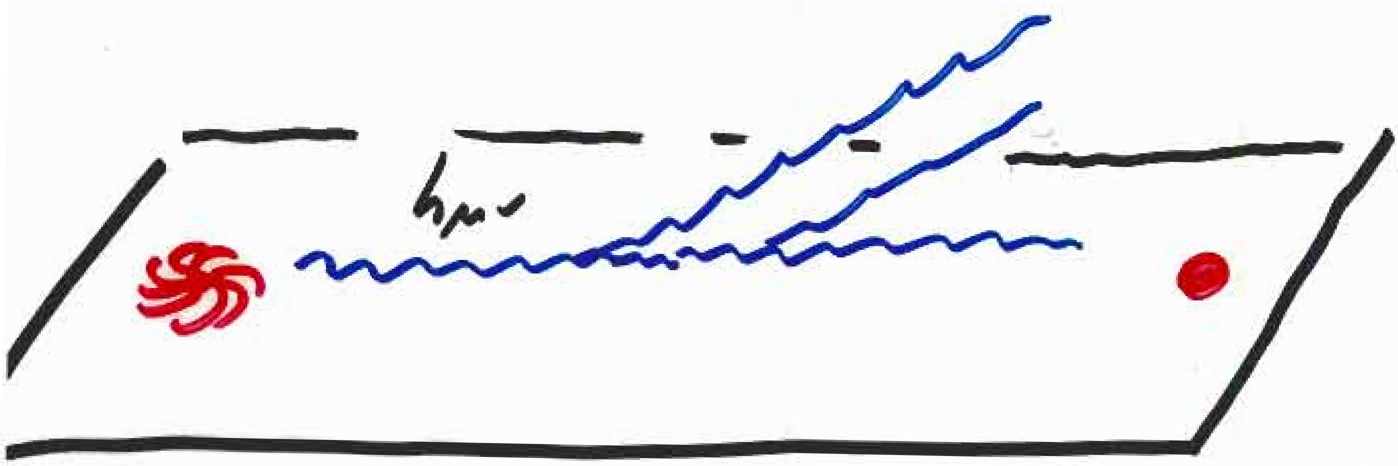
$$g_{\mu\nu} = \partial_\mu X^A \partial_\nu X^B G_{AB}$$



$$M_{p\ell}^2 \int_{3+1} d^4x \sqrt{-g}\; R_{(4)}$$

$$M_{p\ell}^2 \sim (\text{Number of 4D fields}) \times (\text{cutoff})^2$$

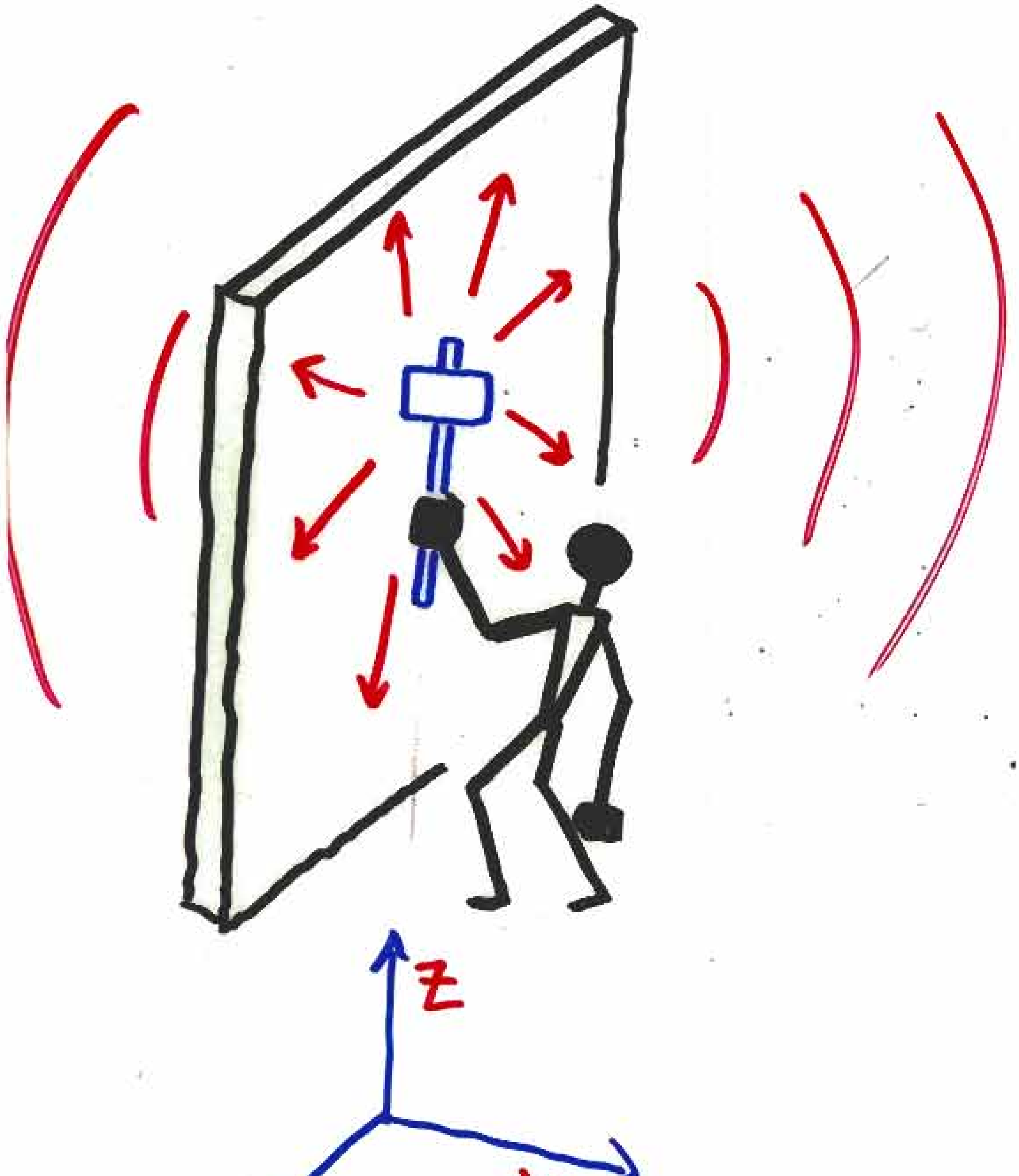
"ESCAPING" GRAVITON



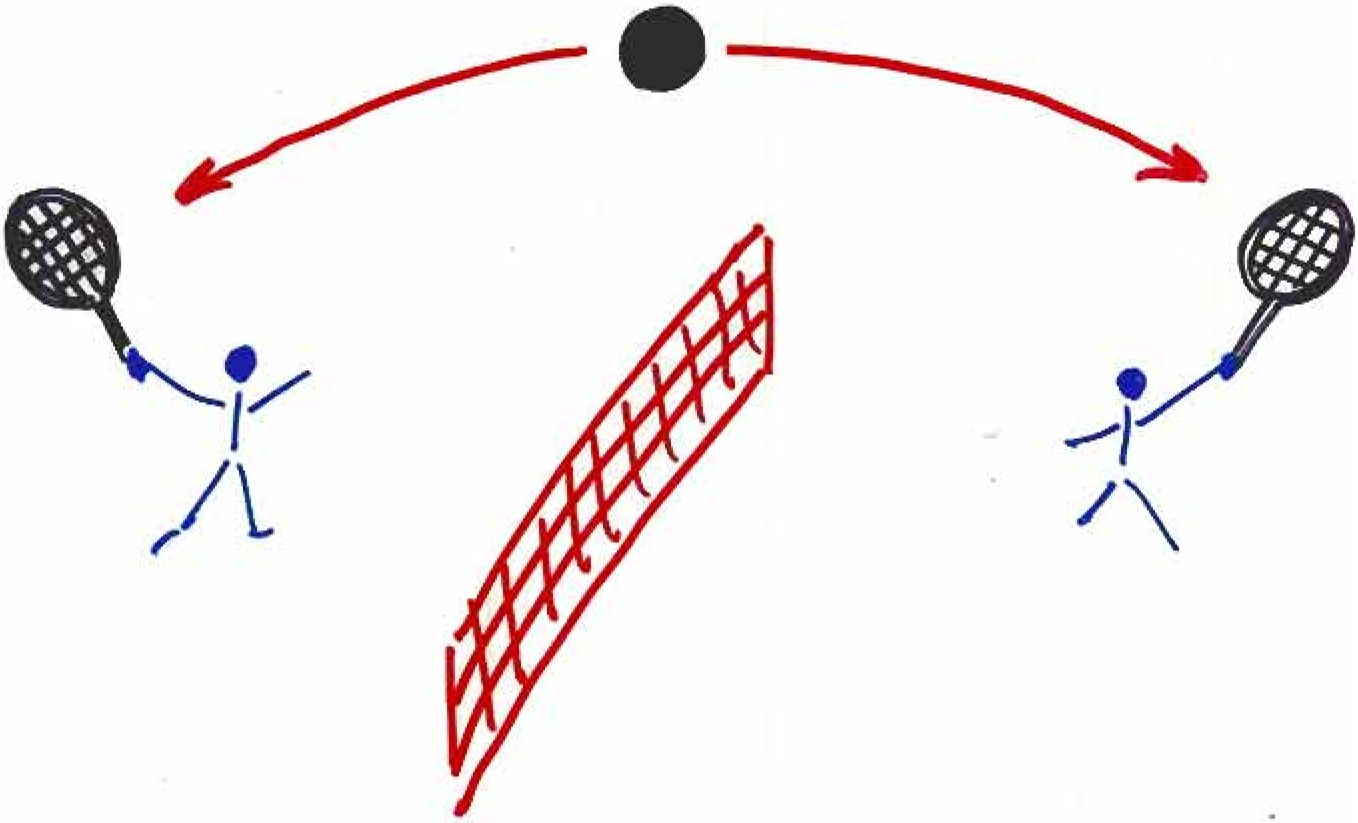
$$\left\{ \delta(y)\, \Box_4 + \frac{1}{r_c}\, \Box_5 \right\} h_{\mu\nu} = 0$$

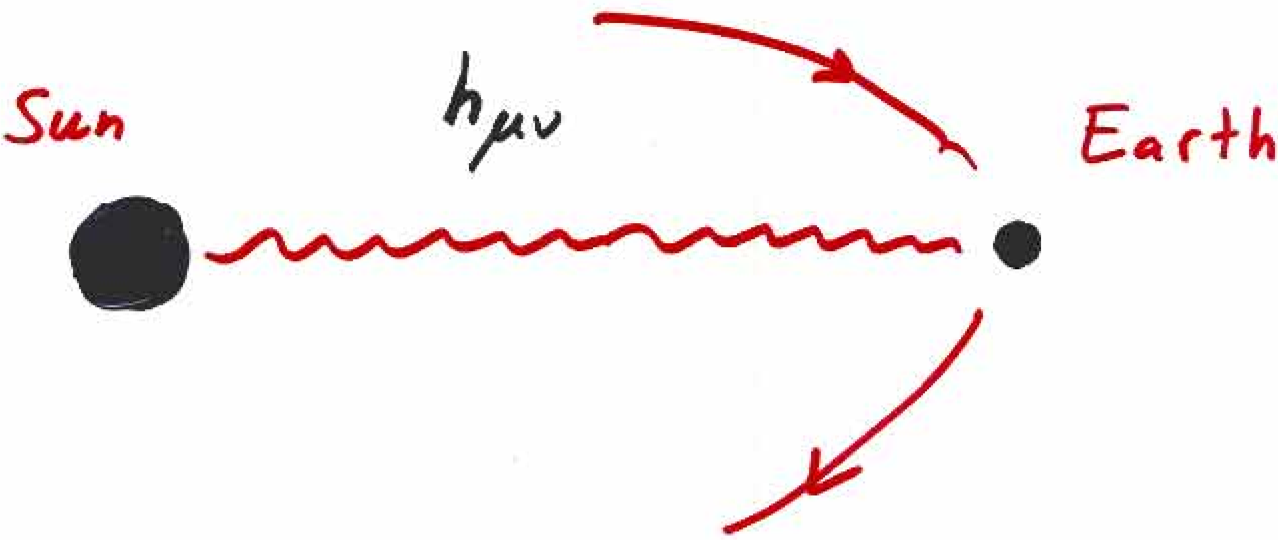
SOUND WAVE

DGP '00



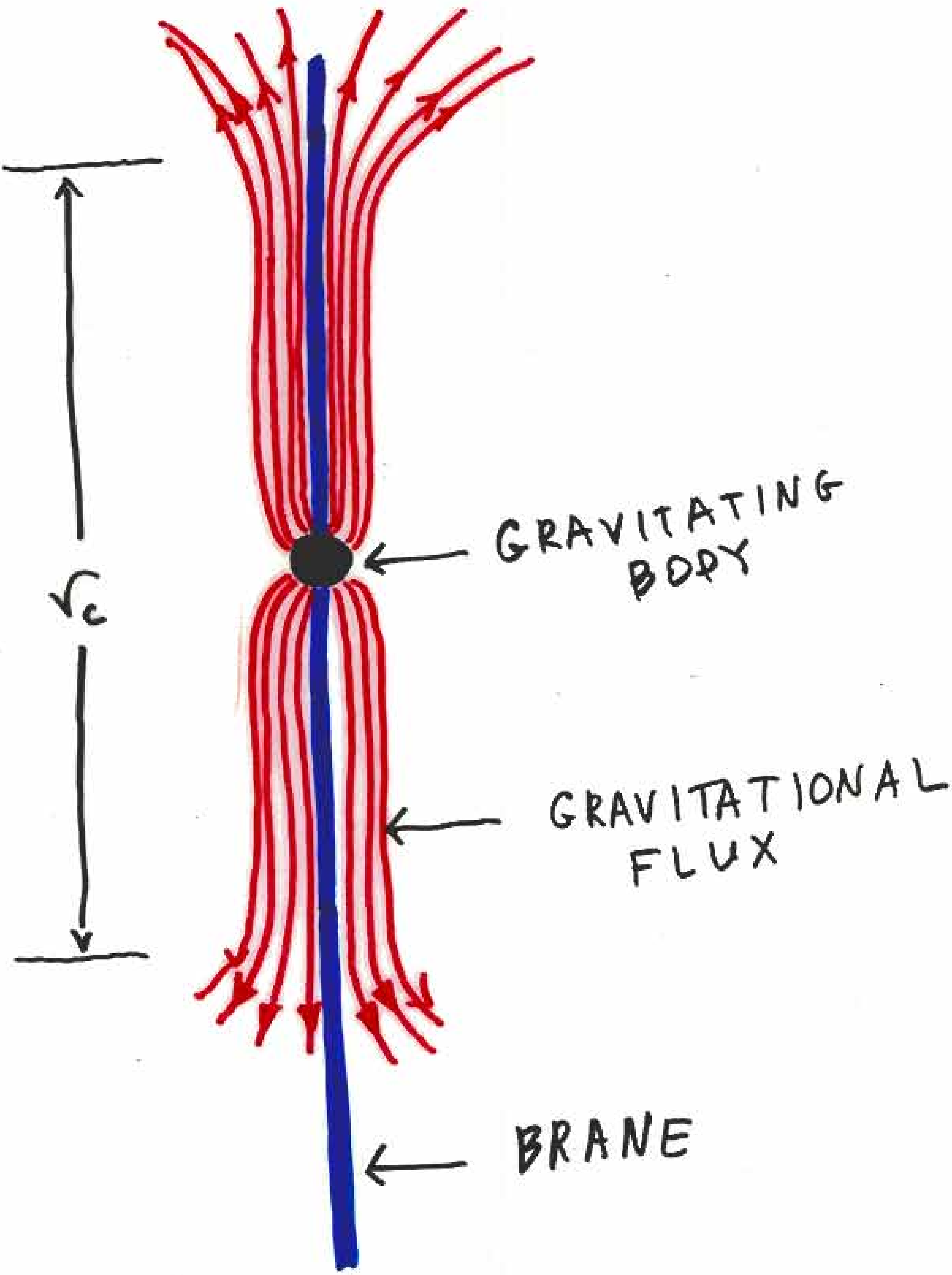
$$\left\{ \delta(y)\,\Box_{2+1} + \frac{1}{r_c}\,\Box_{3+1} \right\} \Psi = \delta^4(x)$$





Sun
$h_{\mu\nu}$
Earth

Flux picture



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.

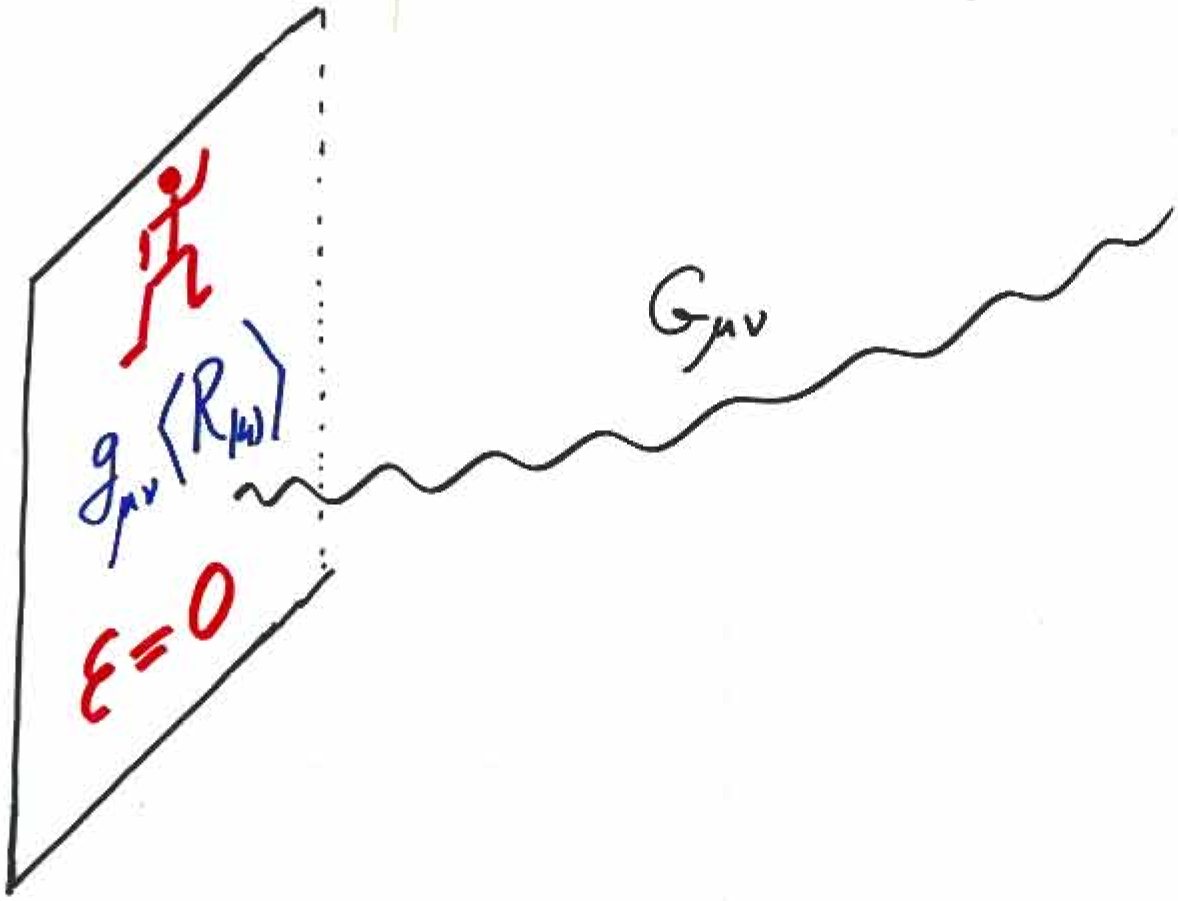
Self-inflating gravity:

Inflating zero-tension brane!

C. Deffayet.
C. Deffayet, G. Gabadadze, G.D.

$$ds^2 = (1 + |y|H)\{dt^2 - e^{Ht} d\vec{x}^2\} - dy^2$$

$\mathcal{E} = 0$, BUT: $\quad H \equiv \frac{\dot{a}}{a} = \frac{1}{r_c}$!



Deffayet, G.D., Gabadadze

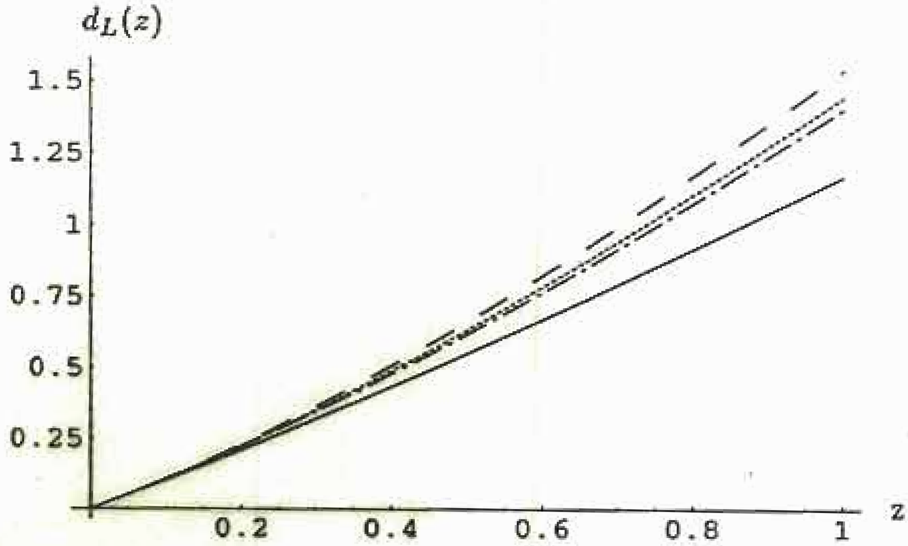


Figure 2: Luminosity distance as a function of red-shift for ordinary cosmology with $\Omega_\Lambda = 0.7, \Omega_M = 0.3, k = 0$ (dashed line), $\Omega_\Lambda = 0, \Omega_M = 1, k = 0$ (solid line), and dark energy with $\Omega_X = 0.7, w_X = -0.6, \Omega_M = 0.3, k = 0$ (dotted-dashed line) and in our model (dotted line) with $\Omega_M = 0.3$ and a flat universe (for which one gets from equation (28) $\Omega_{r_c} = 0.12$ and $r_c = 1.4 H_0^{-1}$).

D., Turner

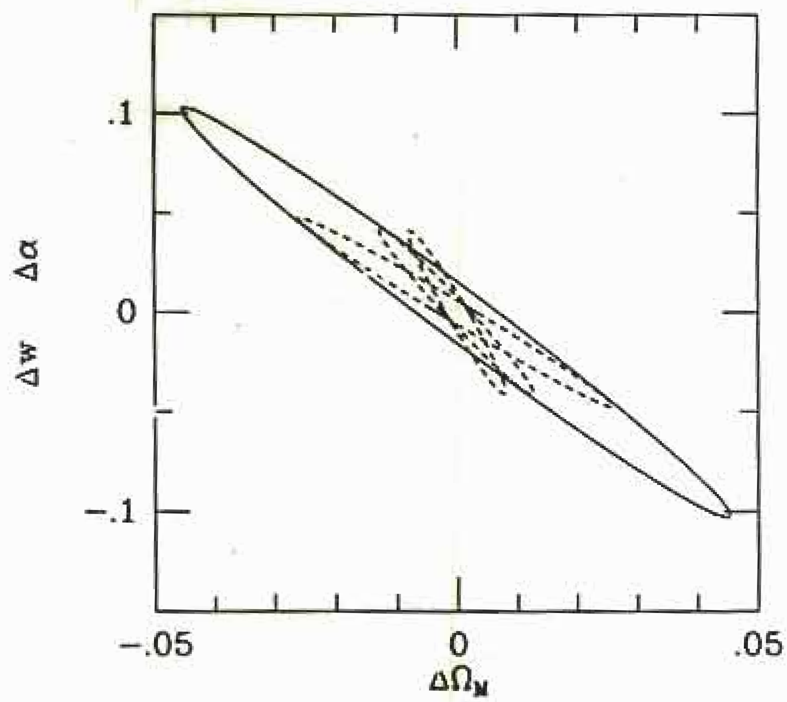


Figure 4: Predicted error ellipses in the $\alpha - \Omega_M$ and $w - \Omega_M$ planes for $w = -1.3, -1.0, -0.7$ (moving counterclockwise) and for $\alpha = 1$ for a SNAP-like supernova experiment, assuming $\Omega_M = 0.33$.

as expected, it is only about twice as large (not quite as large as expected from the rough

Cosmology, stability and other issues on self-accelerated branch

Sahni & Shtanov;

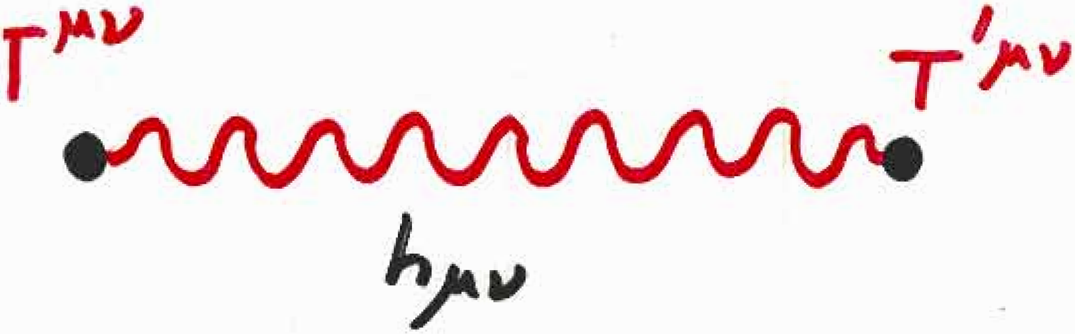
Deffayet;

Lue & Starkman;

Koyama & Kazuya;

Koyama & Kayoko

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:

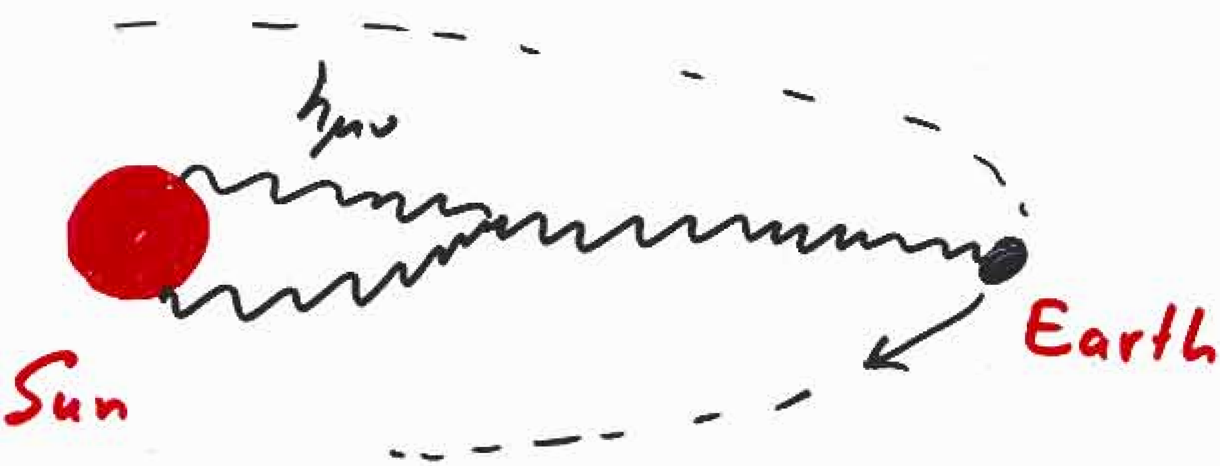
$$A \sim \frac{T'_{\mu\nu}T^{\mu\nu} - \frac{1}{2}T'^{\mu}_{\mu}T^{\nu}_{\nu}}{p^2}$$

HIGH-DIMENSIONAL GRAVITON HAS <u>EXTRA</u> POLARIZATIONS

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

Is this model ruled out?

However:

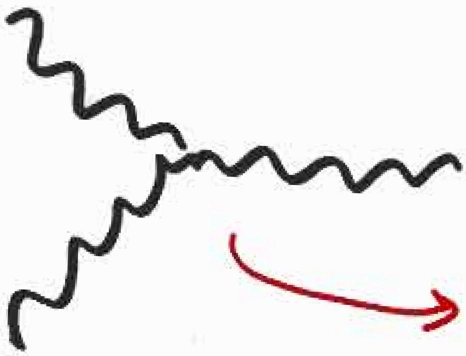


The strong coupling phenomenon in DGP-model

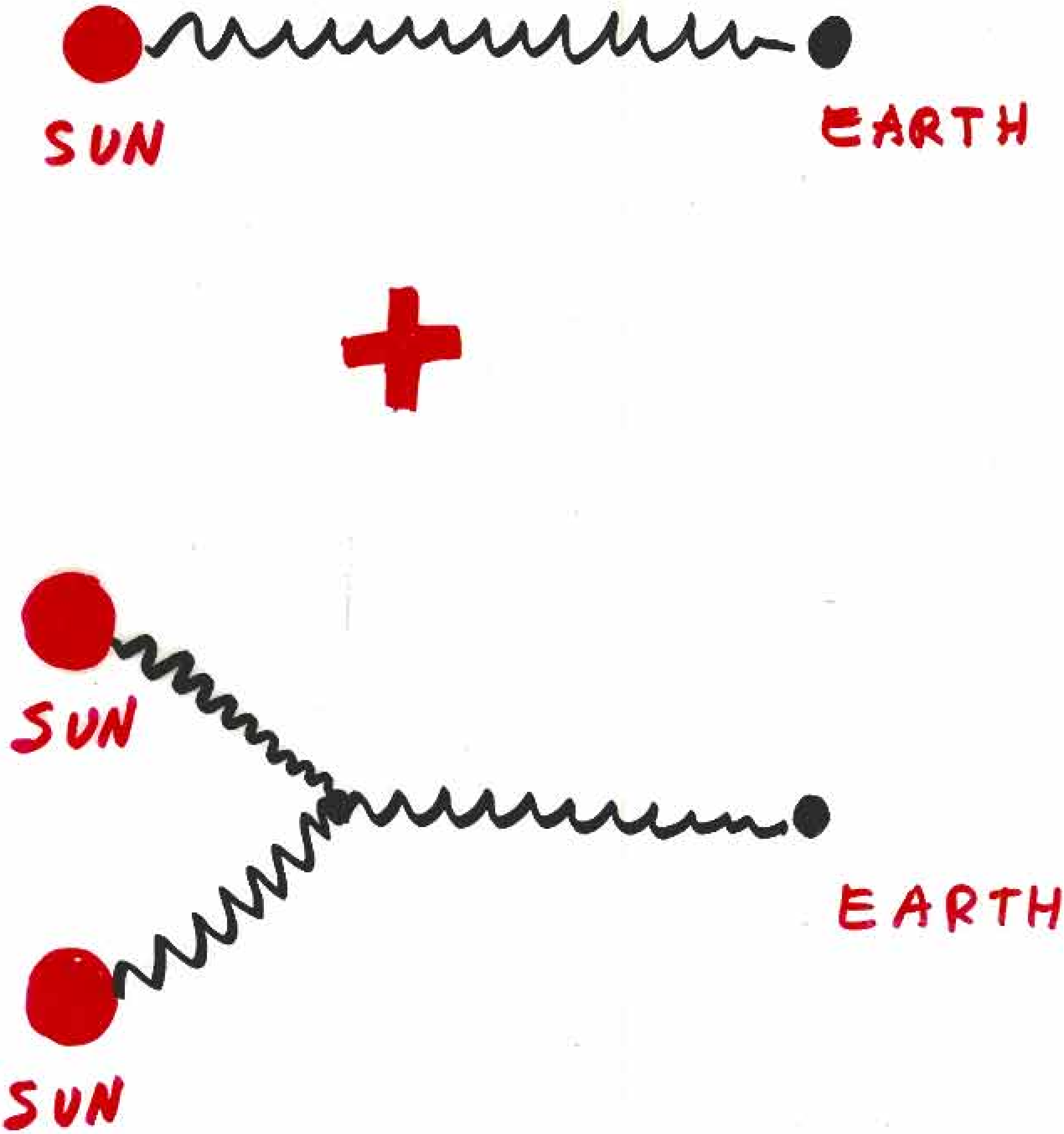
Deffayet, G.D., Gabadadze, Vainshtein (2001)

$$\Delta_{\mu\nu,\alpha\beta} = \frac{\frac{1}{2}\left(\tilde{\eta}_{\mu\alpha}\tilde{\eta}_{\nu\beta} + \tilde{\eta}_{\mu\beta}\tilde{\eta}_{\nu\alpha}\right) - \frac{1}{3}\tilde{\eta}_{\mu\nu}\tilde{\eta}_{\alpha\beta}}{p^2 + p/r_c}$$

$$\tilde{\eta}_{\mu\nu} = \eta_{\mu\nu} + \frac{p_\mu p_\nu}{p/r_c}$$



$$\frac{p^3}{M_P/r_c^2} - \text{singlularity}$$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Non-perturbative solutions:

$$\lim_{r_c \to \infty} = \text{Eeinstein}$$

① Cosmology — Deffayet, G.D., Gabadadze, Vainshtein;

② Cosmic strings — Lue

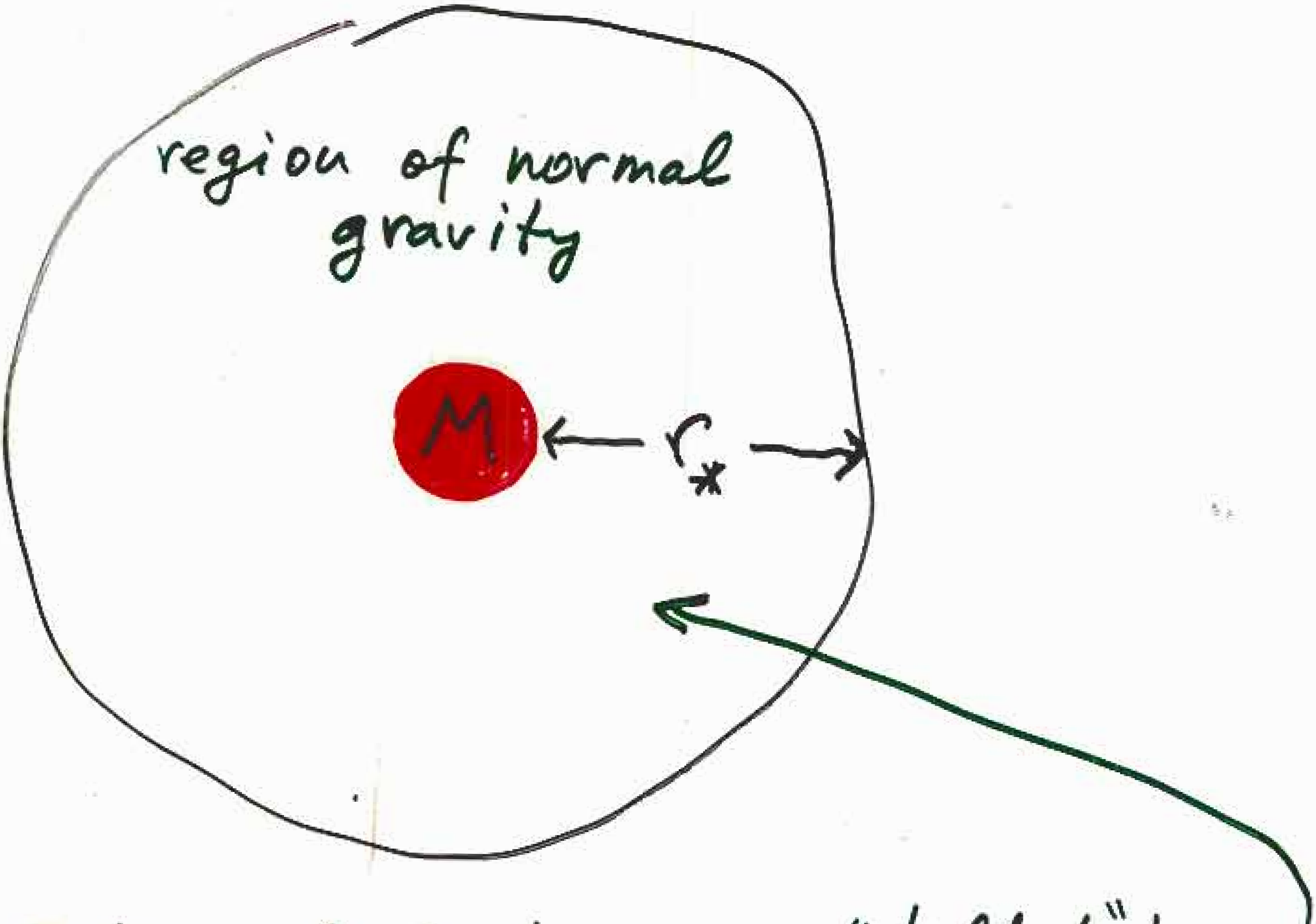
③ Schwarzschild

Gruzinov ($\frac{1}{r_c}$ - expansion);

Gabadadze & Iglesias (Exact);

$r_c \to \infty$ continuity (different approach)

Tanaka



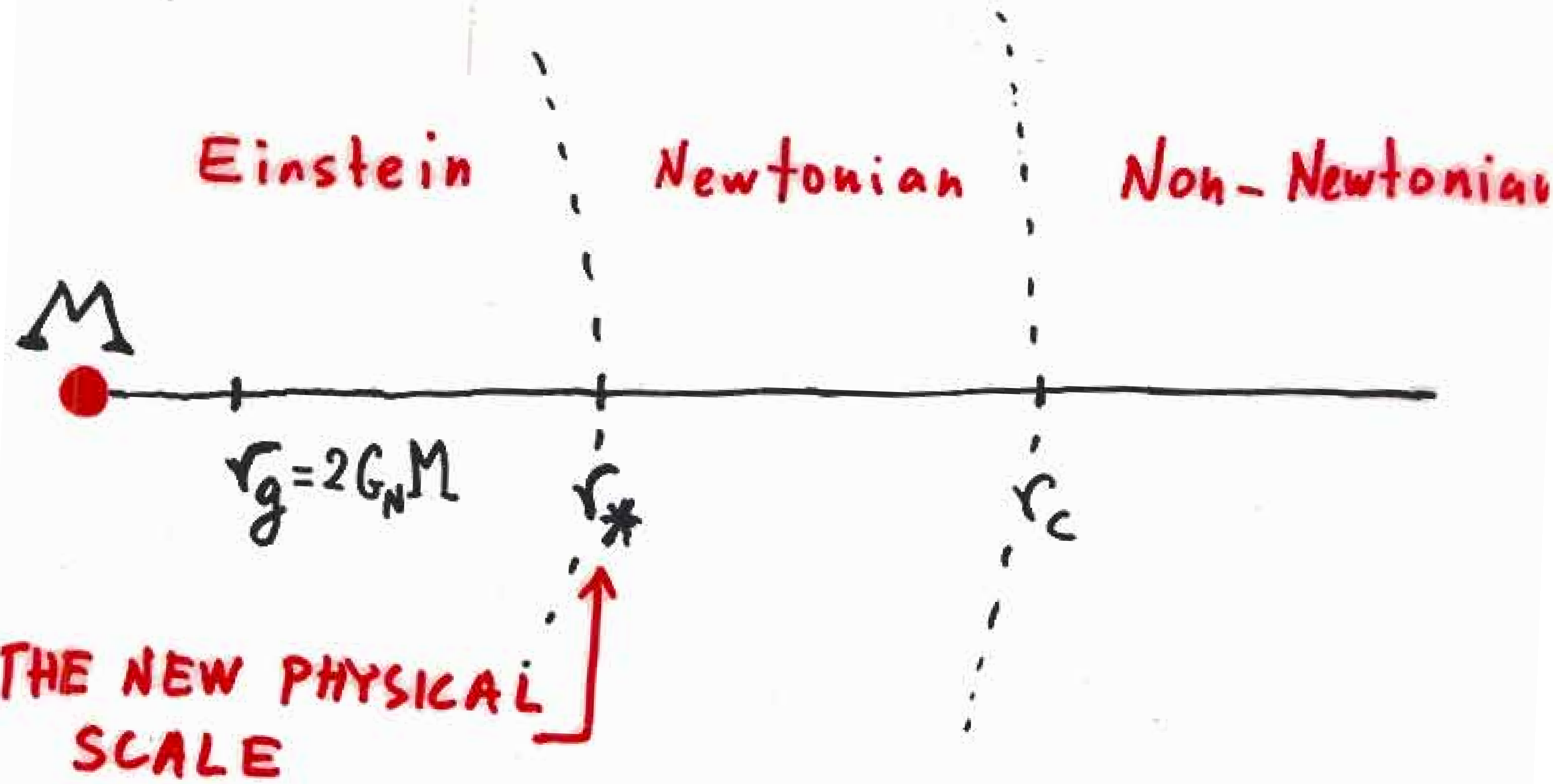
Extra polarizations are "shielded" here

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

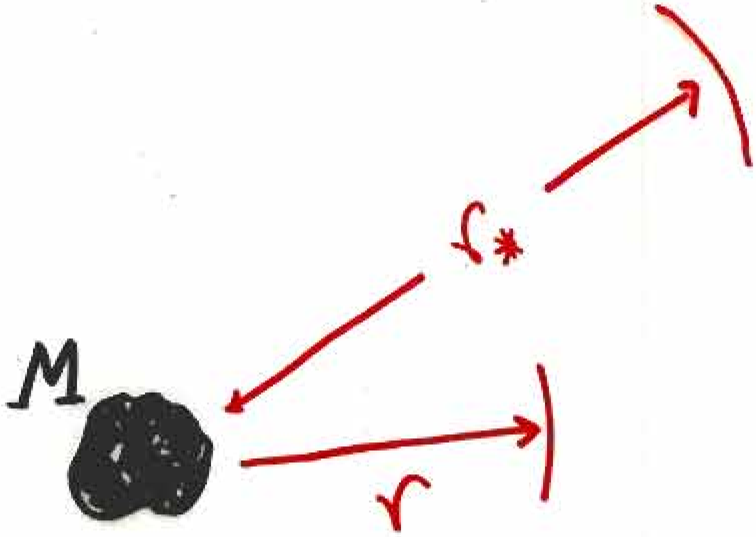
$$r_g \equiv 2 G_N M$$

Corrections to Einstein are Source-dependent

$$\text{Corrections to Einstein} \begin{cases} \neq \dfrac{r}{r_c} \\ = \left(\dfrac{r}{r_*}\right)^{3/2} \end{cases} \qquad r_* \ll r_c$$



$$r_* = \left(r_c^2 r_g\right)^{\frac{1}{3}}$$



$r_g = 2G_N M$

Change of gravitational potential relative to GR

$$\frac{\delta\psi}{\psi} \sim \frac{r}{10^{28}\,\mathrm{cm}}\sqrt{\frac{r}{r_g}}$$

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

Martian ranging: Lue, Starkman

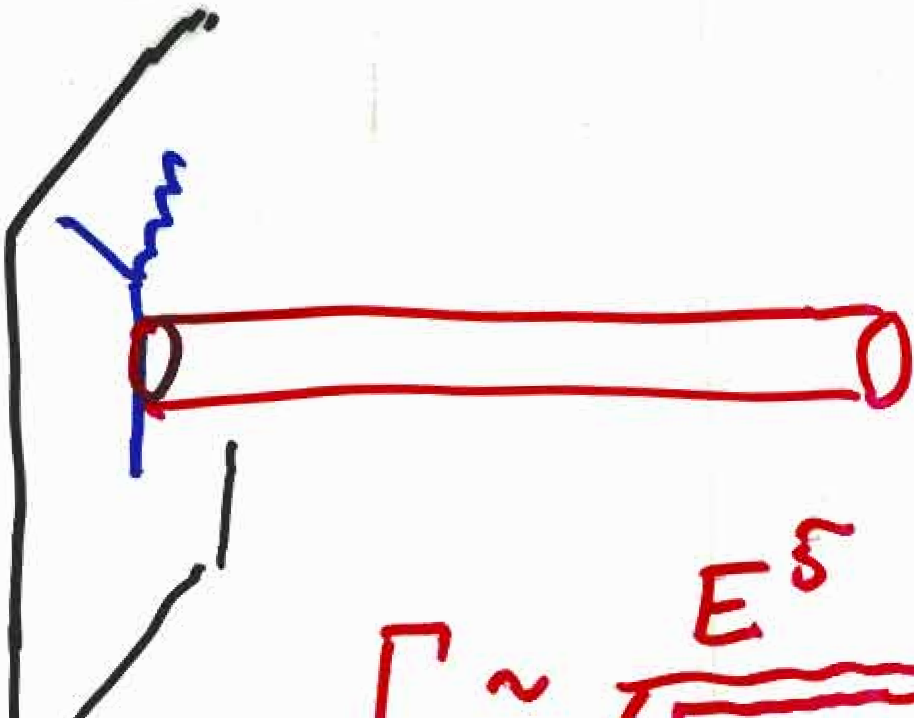
Codimension $N > 1$

$$r_c = \frac{M_P}{M_*^2} \longrightarrow M_* \sim 10^{-3}\,eV$$

$$\downarrow$$

$$r_c \sim H_0^{-1} = 10^{28}\,cm$$

Hagedorn transition at LHC



$$\Gamma \sim \frac{E^5}{\left(\sqrt{M_P M_*}\right)^4}$$

LORENTZ-VIOLATING LARGE DISTANCE MODIFICATION:

SLOWLY INSTANTANEOUS GRAVITY.

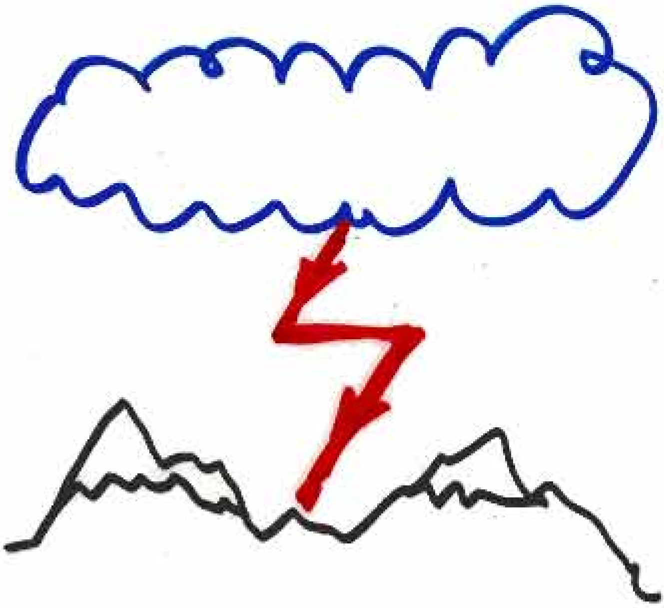
G.D., Papucci, Schwartz; Gabadadze, Grisa

PHOTON EXAMPLE:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m^2 A_j A^j + A_\mu J^\mu$$

$j = 1, 2, 3$

1. WAVES ARE MASSIVE;
2. BUT STATIC FORCE IS COULOMB NOT YUKAWA;
3. ELECTRIC SIGNALS ARE SLOWLY INSTHNTANEOUS



$$\dot{\vec{E}} = \mu m \sin(mt)\,\Theta(t)\,\partial_z \vec{\nabla} \frac{1}{r}$$

for $t < r$