Testing Fundamental Physics with Cosmology and GW

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Gravity is described by General Relativity (GR):

$$S_{\mathrm{EH}} = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} R$$

Uniqueness theorem (Weinberg 1965):

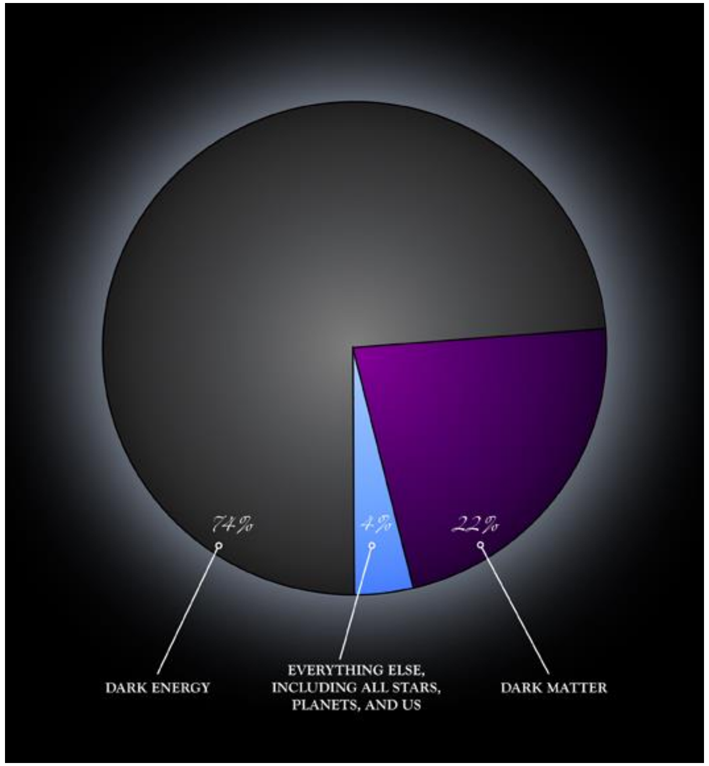
GR is the unique Lorentz invariant theory of massless helicity 2 fields

Lorentz invariance implies the weak equivalence principle (Weinberg 1965) for elementary particles.

$$S_m(\psi_i, g_{\mu\nu})$$

Particles couple to a unique metric.

But no good understanding of dominant phenomena on cosmological scales where both dark matter and dark energy are necessary to explain Baryon Acoustic Oscillations (BAO) or the Cosmic Microwave Background (CMB).



$$S_{\Lambda\mathrm{CDM}} = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(R-2\Lambda)$$

Cosmological constant

The cosmological constant can be replaced by dynamical fields with more fundamental origins:

DARK ENERGY

Most of such extensions involve light scalar fields, for instance:

Massive gravitons have a scalar part

$$5 = 2 + 2 + 1$$

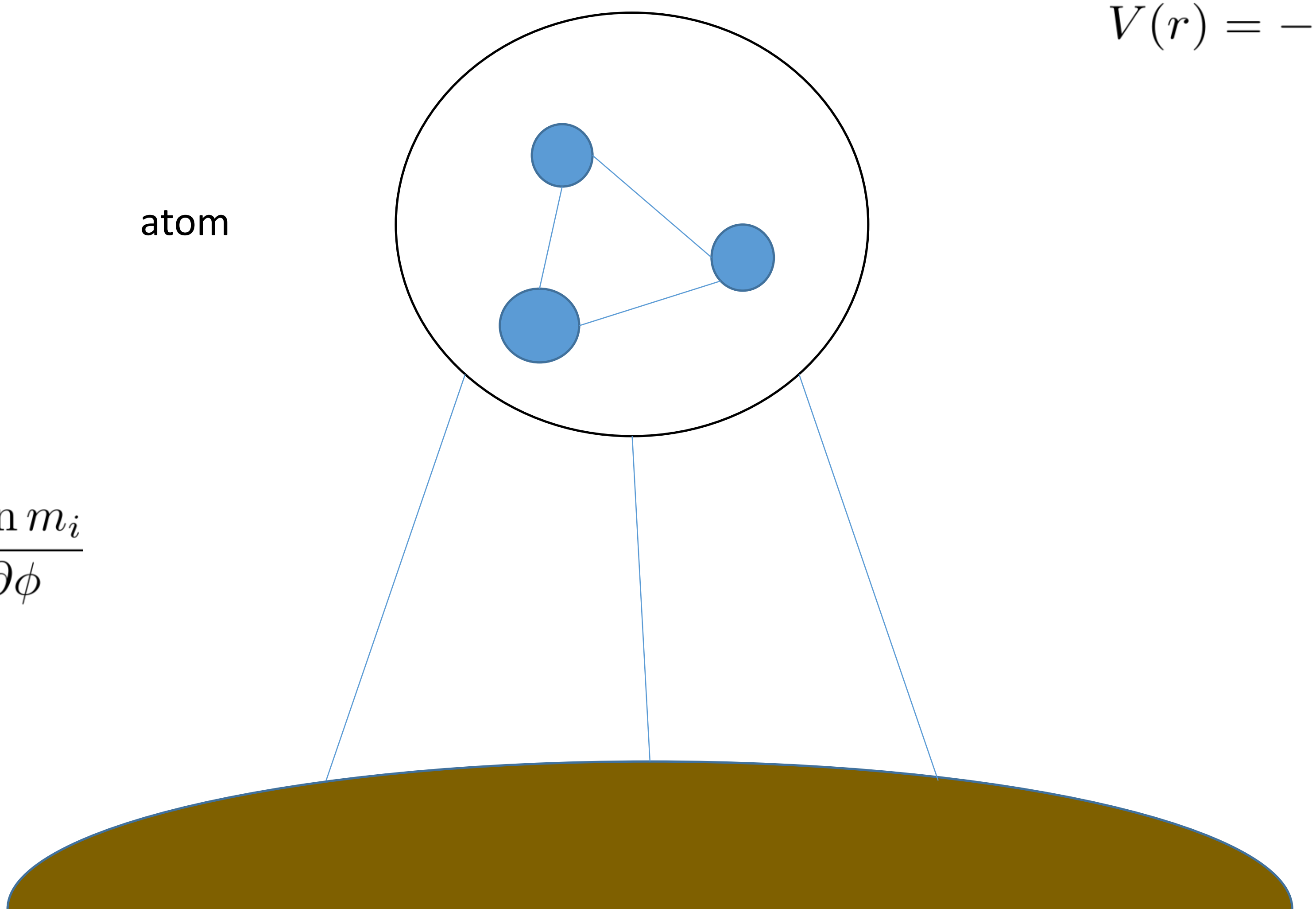
Their interaction with matter generates fifth forces which would have been seen in the solar system.

A scalar field can couple to matter, and different types of matter like baryons (quarks) or leptons (electrons) with a different strength. Such a dependence implies that different atoms fall differently in a gravitational field:

$$V(r) = -\frac{G_N m_1 m_2}{r}(1+\alpha_1\alpha_2)$$

Scalar charges of the interaction bodies.

atom



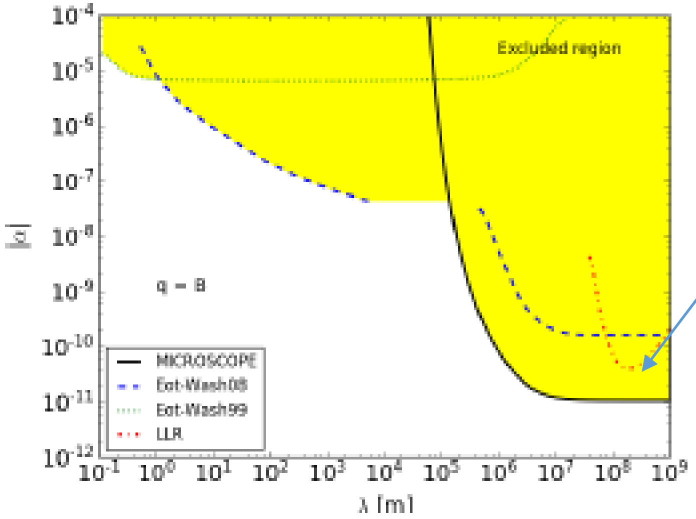
Large body

$$\alpha_i = \frac{m_{\rm Pl}}{\sqrt{2}}\frac{\partial \ln m_i}{\partial \phi}$$

One typical class of models posits that the interaction of the scalar is via the baryonic number:

New Bounds from the Microscope experiment

Strength of the interaction: must be tiny for interactions of long range



One order of magnitude improvement

$$\alpha_i = \alpha(\frac{B}{\mu})_i$$

Range of the scalar interaction

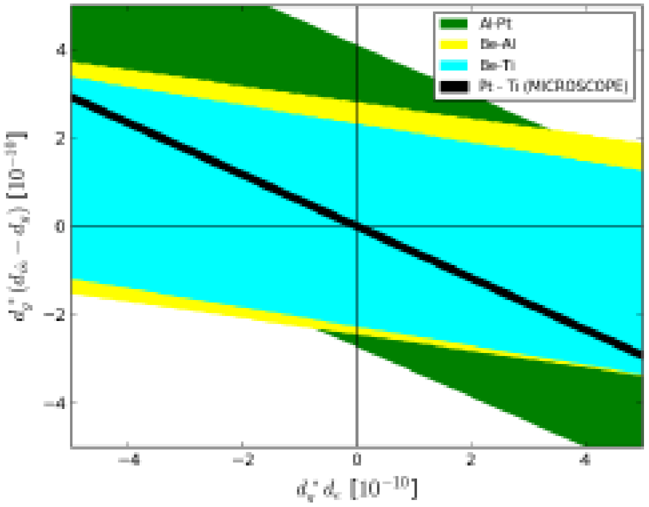
$$\eta_{AB} = 2\frac{|a_A - a_B|}{a_A + a_B}$$

$$\eta_{AB} \sim \alpha_E |\alpha_A - \alpha_B|$$

Eotvos parameter measuring the violation of the weak equivalence principle

Another type of model, called dilatonic, assumes that the scalar couples differently to the gluons, photons, electrons and quarks u and d.

Very small charges



$$\frac{\delta m_{u,d}}{m_{u,d}} \sim d_{u,d} \frac{\phi}{m_{\rm Pl}}$$

$$\frac{\delta \alpha_{QED,QCD}}{\alpha_{QED,QCD}} \sim d_{e,g} \frac{\phi}{m_{\rm Pl}}$$

$$\alpha_i = d_g^\star + ((\bar{d}_m - d_g) Q_m + d_e Q_e)_i$$

$$Q_m = 0.093 - \frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

$$Q_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

Plenty of scalar field models which could play a role in the dynamics of the Universe.

LOOPHOLE: one wants long range interactions on cosmological scales and a coupling to matter which is not tiny.

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Strong deviations from GR in the solar system?

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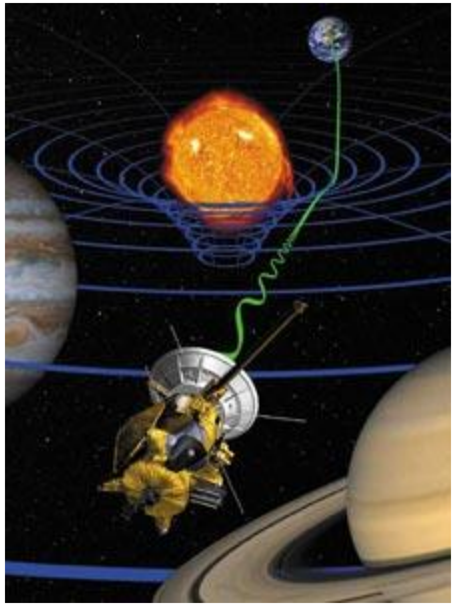
SCREENING



Most of such extensions involve light scalar fields, for instance:

Massive gravitons have a scalar part

Coupled to matter leading to an enhancement of gravity by 4/3.

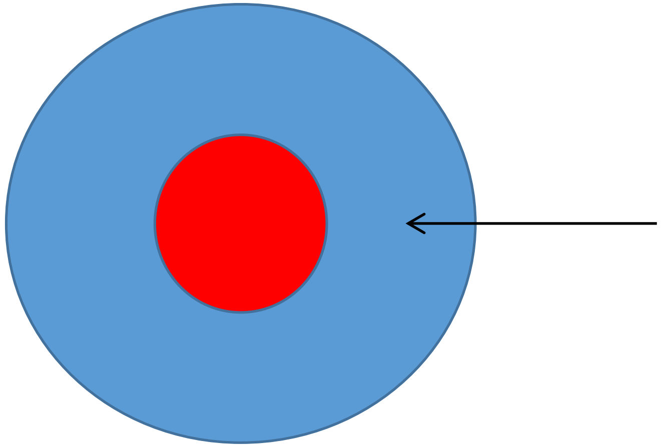
$$5 = 2 + 2 + 1$$

Their interaction with matter generates fifth forces which would have been seen in the solar system.

A simple example: the CUBIC GALILEON

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2\Lambda^3}(\partial\phi)^2\partial^2\phi + \frac{\beta\phi}{M_P}T\,.$$

$\Lambda^3 = m^2 m_{\mathrm{Pl}}$ m graviton mass



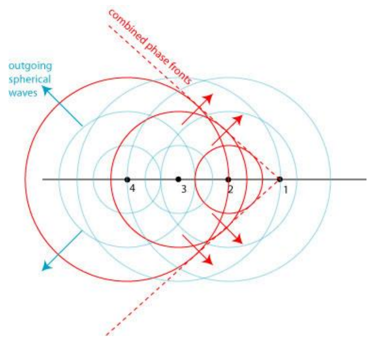
$$\frac{F_\phi}{F_N} = 2\beta^2\left(\frac{r}{R_V}\right)^{3/2}\,.$$

Well inside *the Vainshtein radius*, Newtonian gravity is restored. Well outside gravity is modified.

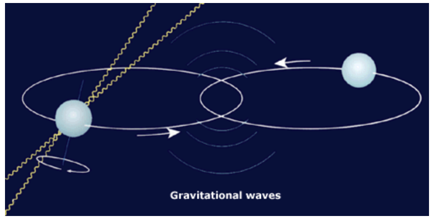
The Vainshtein radius is very large for stars, typically 0.1 kpc for the sun, and a mass for the graviton of the order of the Hubble rate .

Where could we observe modified gravity?

Gravitational waves: modification of the speed of gravitational waves.



Gravitational Cerenkov effect



Binary pulsars

More stringent: neutron merger constraint

For the generalised Horndeski models (see Langlois' talk):

$$\mathcal{L} = K(\phi, X) - G_3(\phi, X)D^2\phi + G_4(\phi, X)R + G_{4,X}((D^2\phi)^2 - (D_\mu D_\nu \phi)^2)$$
$$-\frac{1}{6}G_{5X}((D^2\phi)^3 - 3D^2\phi(D_\mu D_\nu \phi)^2 + 2D^\mu D_\alpha \phi D^\alpha D_\beta \phi D^\beta D_\mu \phi)$$

where X is the kinetic term of the scalar field. The scalar field ϕ is screened by the Vainshtein mechanism.

Is the speed of gravitons affected by the screening locally?

Inside the Vainshtein radius of quartic Galileons, IF spatial gradients are larger than time derivatives:

$$c_T^2 = 1 - \frac{2XG_{4,X}}{G_4}$$

Where the gradient is essentially constant… and very small… implying that the speed of gravity waves would be screened…

$$X = -\frac{\Lambda^4}{2}\left(\frac{c_{0b}M}{8\pi m_{\rm Pl}c_4}\right)^{2/3}, \quad |\Delta c_T^2| \le 10^{-30}$$

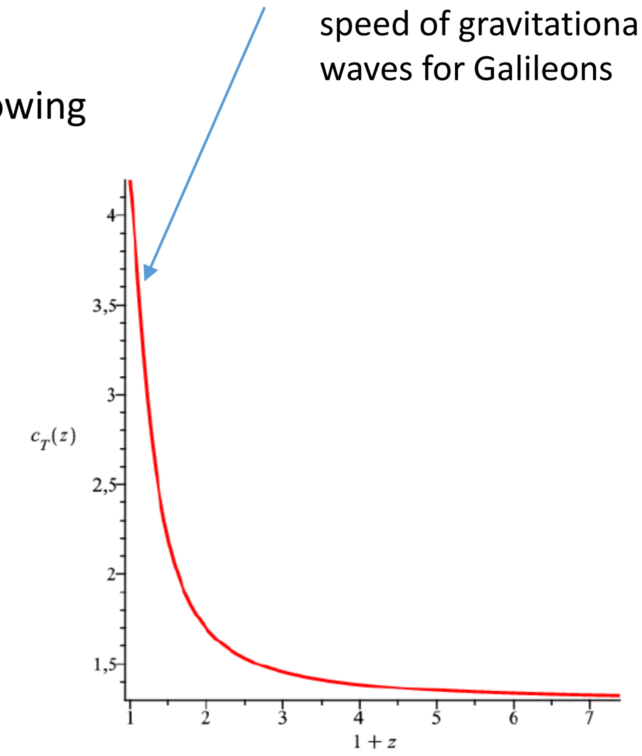
Unfortunately, the time derivatives are smaller than the gradients when the following condition is verified:

$$R_V H_0 \gg 1$$

This is violated for masses of around one solar mass as the Vainshtein radius is much smaller than the cosmological horizon!

$$R_V H_0 \sim 10^{-7}$$

Large values of the speed of gravitational waves for Galileons



Bimetric Gravity

One way to construct a non-linear version of massive gravity involves two dynamical metrics:

$$S = \int d^4x (e_1 \frac{R_1}{16\pi G_N} + e_2 \frac{R_2}{16\pi G_N} + \Lambda^4 \sum_{ijkl} m_{ijkl} \epsilon_{abcd} \epsilon^{\mu\nu\rho\sigma} e^{ai}_{\mu} e^{bj}_{\nu} e^{ck}_{\rho} e^{dl}_{\sigma})$$

where the graviton mass is of order:

$$m_g^2 \sim \frac{\Lambda^4}{m_{\mathrm{Pl}}^2} \sim H_0^2$$

New link between *dark energy* and the *mass of the graviton*

Because of the presence of two dynamical metrics, there are two types of gravitational perturbations of space-time. In particular, in a Minkowski background, there is one massive and one massless graviton. In a cosmological FRW background, the two waves are coupled, where the two metrics are:

$$ds_1^2 = a_1^2(-d\eta^2 + d\vec{x}^2) \qquad ds_2^2 = a_2^2(-b^2 d\eta^2 + d\vec{x}^2)$$

$$\frac{d^2\bar{h}_1}{d\eta^2} - \Delta\bar{h}_1 + (M_{11}^2 - \frac{1}{a_1}\frac{d^2 a_1}{d\eta^2})\bar{h}_1 + M_{12}^2\bar{h}_2 = 0$$

$$\frac{d^2\bar{h}_2}{d\eta^2} - b^2\Delta\bar{h}_2 + (M_{22}^2 - \frac{b^{1/2}}{a_2}\frac{d^2(a_2 b^{-1/2})}{d\eta^2})\bar{h}_2 + M_{21}^2\bar{h}_1 = 0$$

Notice that one of the waves has a speed which is not unity when b is not equal to one.

The propagation of these waves depends on the background cosmology which depends intrinsically on the coupling to matter of the two metrics. The coupling to matter is determined by the combined vielbein, the most general and "healthy", i.e. which does not lead to ghost-like instabilities, combination at low energy:

$$e^a_\mu = \beta_1 e^a_{1\mu} + \beta_2 e^b_{2\mu}$$

$$3H_1^2 m_{\rm Pl}^2 = \beta_1 \frac{a_J^3}{a_1^3}\rho + 24\Lambda^4 m^{1jkl}\frac{a_j a_k a_l}{a_1^3}$$

$$\frac{3H_2^2 m_{\rm Pl}^2}{b^2} = \beta_2 \frac{a_J^3}{a_2^3}\rho + 24\Lambda^4 m^{2jkl}\frac{a_j a_k a_l}{a_2^3}$$

From which one constructs the Jordan metric:

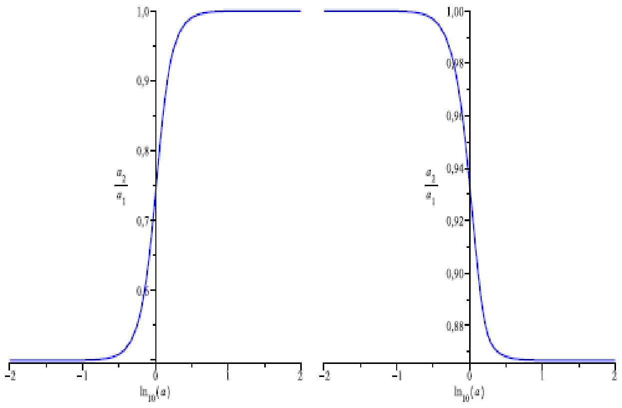
$$g_{\mu\nu} = \eta_{ab} e^a_\mu e^b_\mu$$

The Raychaudhuri equations imply that there are two branches of solutions, one cosmological such that:

$$b = \frac{a_2 H_2}{a_1 H_1}$$

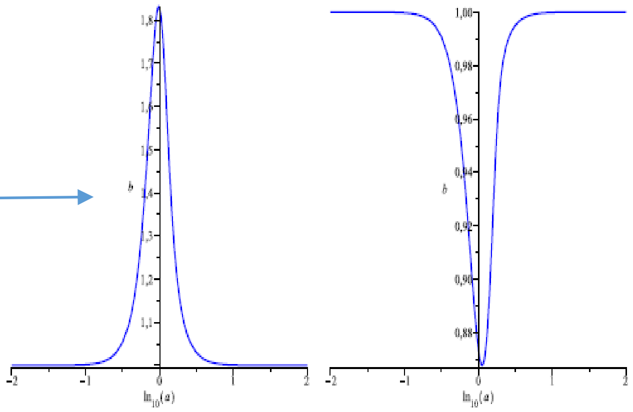
On this branch, the ratio between the two scale factors goes to a constant in the matter, radiation and dark energy eras, with **b=1 in each case**. This ratio determines the speed of the two gravitons.

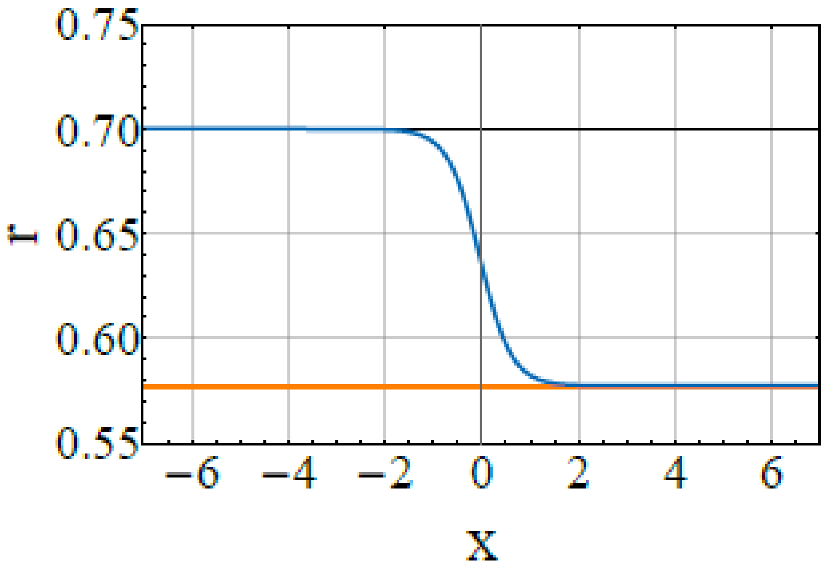
Variation of r=a2/a1 as a function of the Jordan frame redshift



Variation of b as a function of the Jordan frame redshift

Notice that b only differs from one in the recent Universe





Models with eithers all m's=1 and different couplings or same coupling and one differing m.

In the matter and radiation eras, the ratio between the scale factors converges to

$$r = \frac{a_2}{a_1} \to \gamma = \frac{\beta_2}{\beta_1}$$

In the dark energy era, in the far future, the same ratio converges to a constant too

$$r = \frac{m^{2ijk} a_i a_j a_k}{m^{1ijk} a_i a_j a_k}$$

The time evolution of r is monotonic, implying that to maintain b=1 throughout the whole history of the Universe one must impose a constraint on the coefficients:

$$a_2 = \gamma a_1 \to \gamma = \frac{m^{2ijk} a_i a_j a_k}{m^{1ijk} a_i a_j a_k}$$

This is an algebraic equation for γ

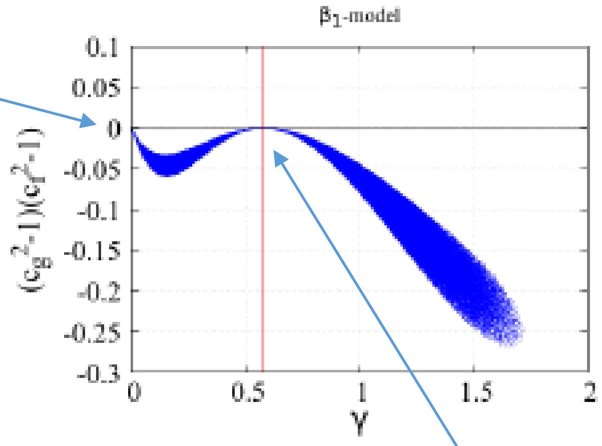
The detection of both the neutron star merger GW170817 and its electromagnetic counterpart gives us a much stronger constraint on the speed of gravitational waves. This should be compared to the speed of light as propagating along the Jordan metric:

$$c = \frac{\beta_1 a_1 + b\beta_2 a_2}{\beta_1 a_1 + \beta_2 a_2}$$

To be compared to the speed of the two gravitons 1 and b.

One can impose both the background cosmology constraints and the GW one. Typically c must be close to either 1 or b at the 10^{-15} level:

Singly coupled model

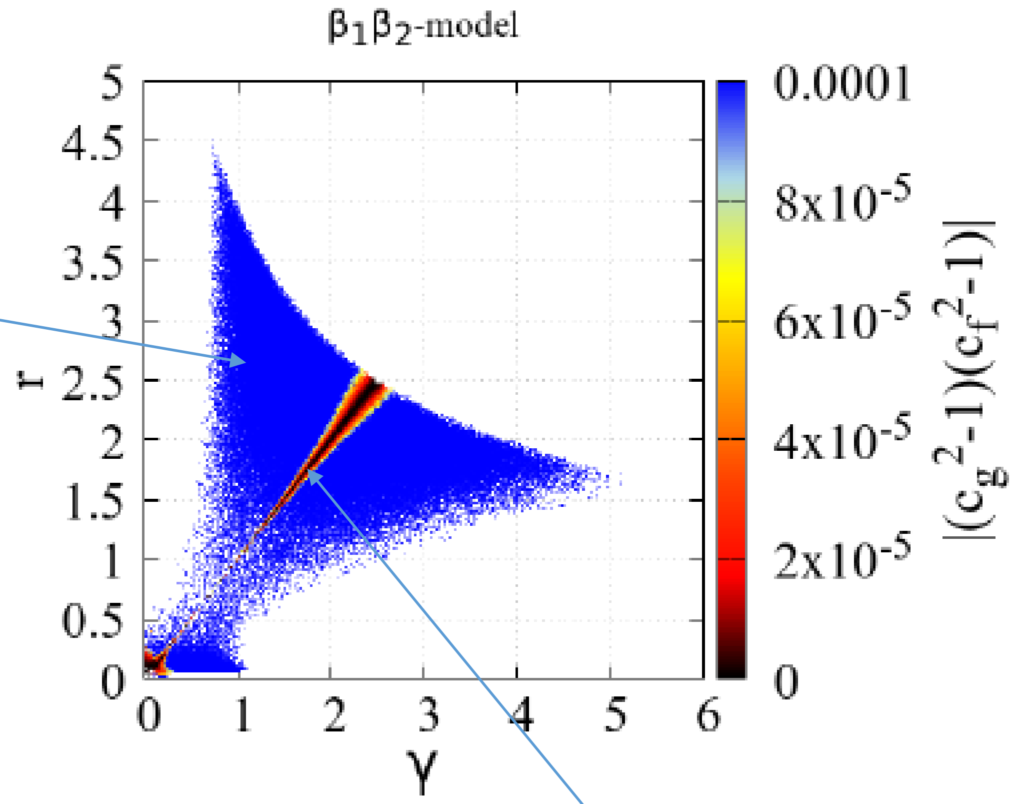


Here a model with only one $m_{1112} \neq 0$

Model with $r = \gamma = \frac{1}{\sqrt{3}}$

When more than one coupling are turned on, one can verify that the allowed models by GW accumulate along the $r = \gamma$ line.

Background cosmology



The GW constraint gives a line in the parameter space.

Great times for the GW-cosmology connection!

Are these results valid? There are several provisos:

1) The theory has a strong coupling scale of order:

$$\Lambda_3 = (m^2 m_{\rm Pl})^{1/3}$$

which implies that for redshifts before BBN and for scales less than 1000 km's, the theory may require a UV completion. Hence no possibility of studying the complete merging of astrophysical objects.

2) The theory needs a UV completion above the strong coupling scale. Such a UV completion might have new degrees of freedom in particular generate a scalar charge for compact bodies. This could generate dipolar radiation on top of the quadrupolar one.