Title: Aspects of Galileon Cosmology

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Abstract: <p>I will discuss the cosmology of galileon models with a Minkowski limit and discuss whether they can account for the currently observed cosmological model. The full galileon model predicts the speed of gravitational waves to be different from that of photons. I will discuss this and compare with observations. I will then discuss a subdominant galileon model which is compatible. Finally I will discuss the shape dependence of screening in galileon models, showing that the fifth force is unscreened for planar objects.</p>

Aspects of Galileon Cosmology

A.C. Davis

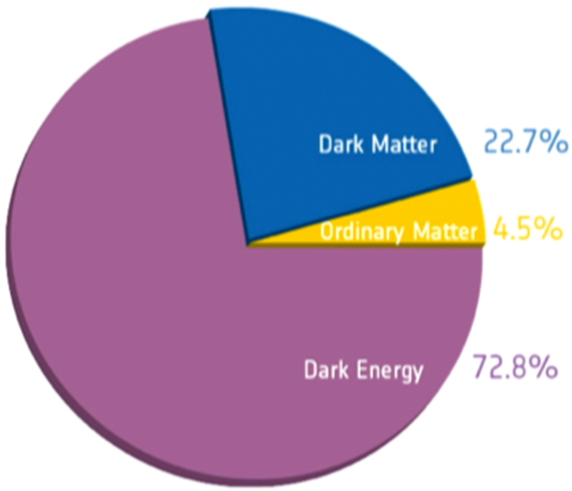
Cosmology of Galilieons coupled to matter	with Philippe Brax, Clare Burrage, and Guilia Gubitosi	1411.721
Graviton Speed	with Philippe Brax and Clare Burrage	1510.03701
Shape Dependence	with Jolyon Bloomfield and Clare Burrage	1408.4759

Observations the Universe is undergoing accelerated expansion today.

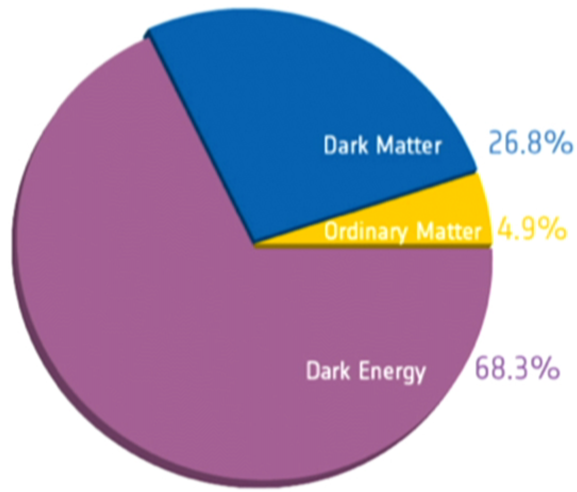
Why?

Cosmological constant? Dark Energy --
Modified Gravity?

Modification of Gravity on large enough scales



Before Planck

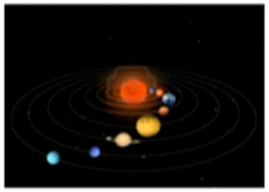


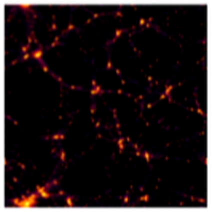
After Planck

What is dark energy?

Λ or modified gravity?

GRAVITY ACTS ON ALL SCALES





Looking for extensions of General Relativity valid from small to large scales.

Modifications result a scalar field and a fifth force

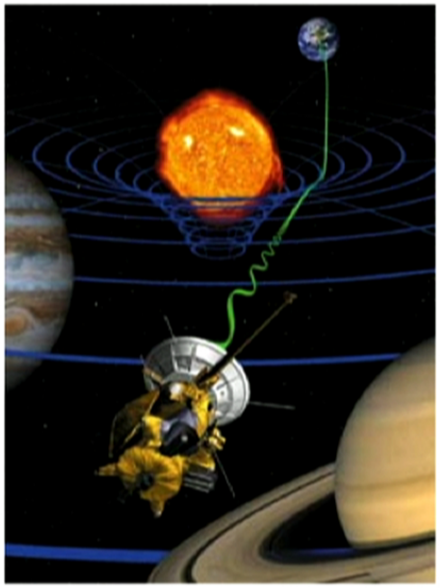
Deviations from Newton's Laws parametrised by

$$\Phi_N = -G_N/r(1 + 2\beta^2 e^{-r/\lambda})$$

First term gives Newton's inverse square law, second term is deviation from standard gravity

tightest constraint comes from satellite experiments

$$\beta^2 \leq 4 \cdot 10^{-5}$$



SCREENING

Around a background configuration
and linearising we have

Main screening mechanisms can be written as

$$\mathcal{L} \supset -\frac{Z(\phi_0)}{2}(\partial\delta\phi)^2 - \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T \ ,$$

The Vainshtein mechanism reduces the coupling to matter by increasing Z

The Damour Polyakov mechanism reduces the coupling β

The chameleon mechanism increases the mass

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The Vainshtein mechanisms can be easily analysed:

Effective Newtonian potential:

$$\Psi = (1 + \frac{2\beta^2(\phi)}{Z(\phi)})\Phi_N$$

For theories with second order equations of motion:

$$Z(\phi) = 1 + a(\phi)L^2\frac{D^\mu D_\mu \phi}{m_{\rm Pl}} + b(\phi)\frac{(\partial\phi)^2}{M^4} + \dots$$

Vainshtein

K-mouflage

$$M^4 \sim 3H_0^2 m_{\rm Pl}^2, \quad L \sim H_0^{-1}$$

Cosmological choice

Galileon invariance

$$\partial_\mu \phi \to \partial_\mu \phi + c_\mu$$

Galileon employs Vainshtein Screening and highly non-linear Lagrangian, but equations of motion only have second order time derivatives

$$\mathcal{L} = -\frac{c_2}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{c_4}{\Lambda^6}\mathcal{L}_4 - \frac{c_5}{\Lambda^9}\mathcal{L}_5 + \sum_i \frac{c_0^i \phi}{m_{\rm Pl}} T_i - \sum_i \frac{c_G^i}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi T_i^{\mu\nu} \ ,$$

where c_0 and c_G are the conformal and disformal couplings

we take $\Lambda^3 = H_0^2 m_{\rm Pl}$ to be of cosmological interest

and $c_2 > 0$ to avoid ghosts in Minkowski space

The coupling to the metric is $\tilde{g}^i_{\mu\nu} = A^i(\phi) g_{\mu\nu} + \frac{2}{M_i^4}\partial_\mu\phi\partial_\nu\phi$. with $A^i(\phi) = 1 + \frac{c_0^i\phi}{m_{\rm Pl}}$

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For c3 non-zero the spherically symmetric solution is

$$\frac{d\phi}{dr} = -\frac{\Lambda^3 r}{4}\left(1-\sqrt{1+\left(\frac{R_*}{r}\right)^3}\right) ,$$

Non-linearities dominate inside the Vainshtein radius to screen the fifth force

$$R_* = \frac{1}{\Lambda}\left(\frac{c_0^b m}{2\pi c_3 m_{\rm Pl}}\right)^{1/3} \qquad \frac{F_\phi}{F_N} = (c_0^b)^2\left(\frac{r}{R_*}\right)^{3/2}$$

Both conformal and disformal couplings to matter are severely constrained.

c_0 leads to large variations in particle masses when coupled to baryons

c_G coupled to baryons is constrained by LHC and to photons by variation of the speed of light

giving the duality relation $d_L = \left(\frac{c_{\rm obs}}{c_{\rm emit}}\right)^2 (1+z)^2 d_A$

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Cosmology

Take universal conformal coupling to matter; baryons to be disformally decoupled whilst CDM and photons have the same coupling

details are very technical and not displayed, see 1411.721

Impose the Friedmann equation and the no-ghost relation between parameters.

defining $g_{eff} \equiv \frac{G_{eff}}{G_N}$ the growth of structure becomes

$$\delta'' + \left(2 + \frac{\bar{H}'}{\bar{H}}\right)\delta' - \frac{3}{2} g_{eff}\delta = 0$$

and impose the sound speed $c_s^2 > 0$ to avoid instabilities

Exploring the parameter space we find

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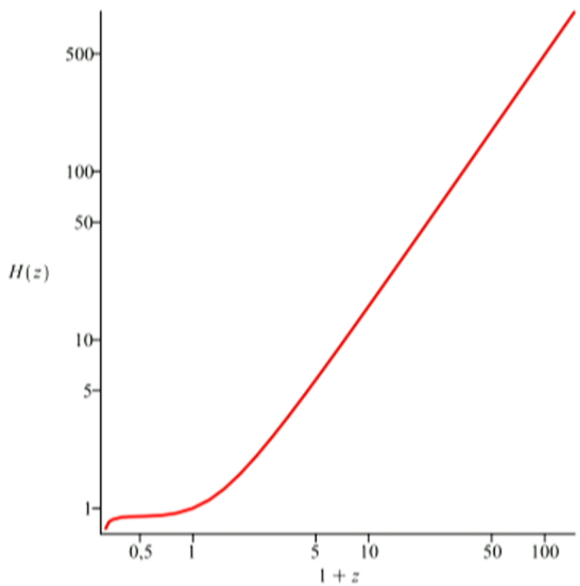
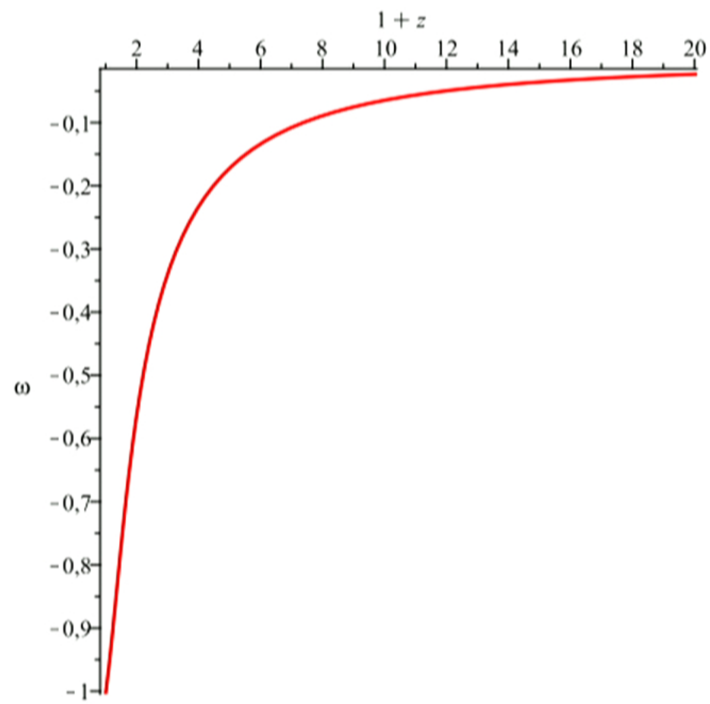
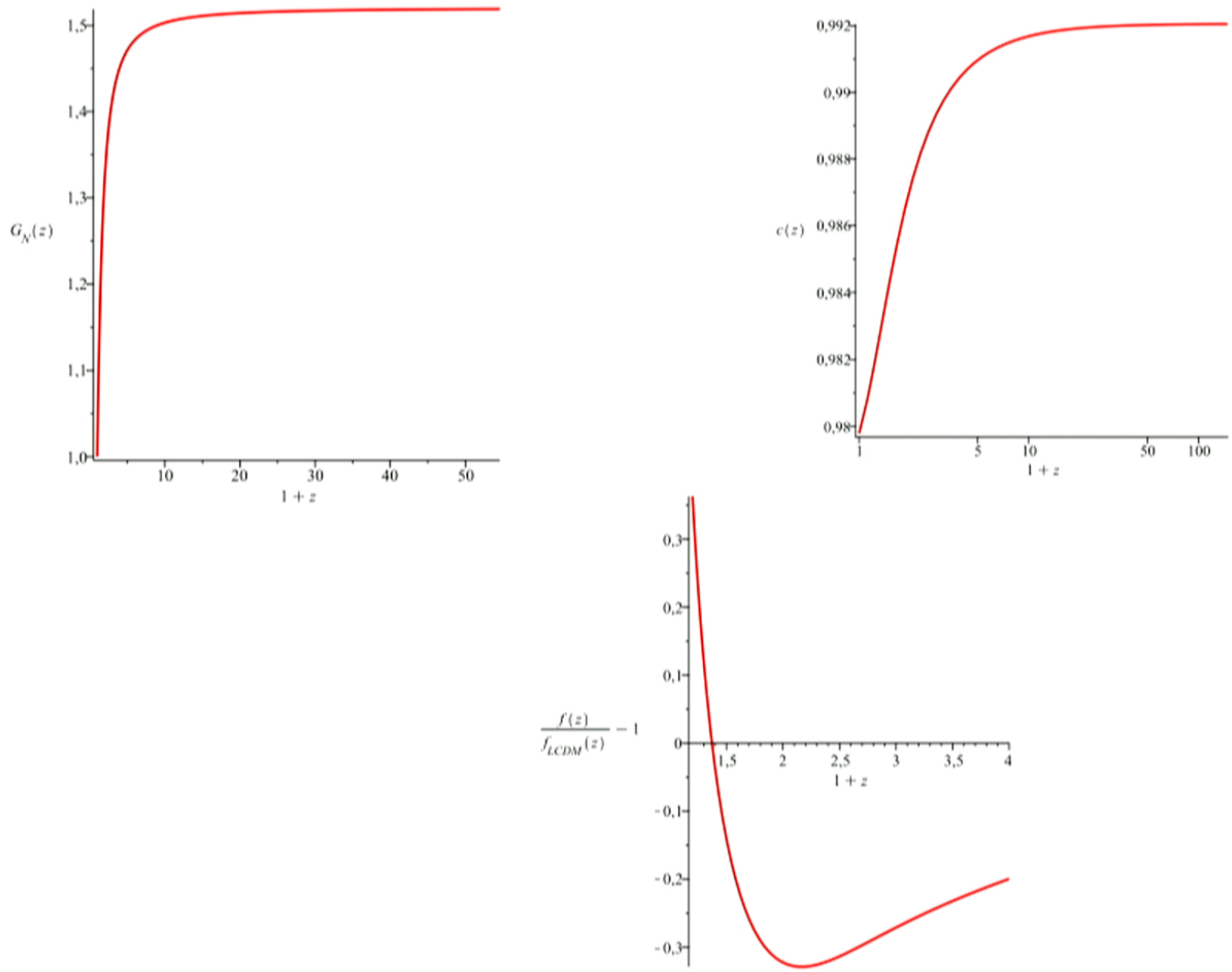
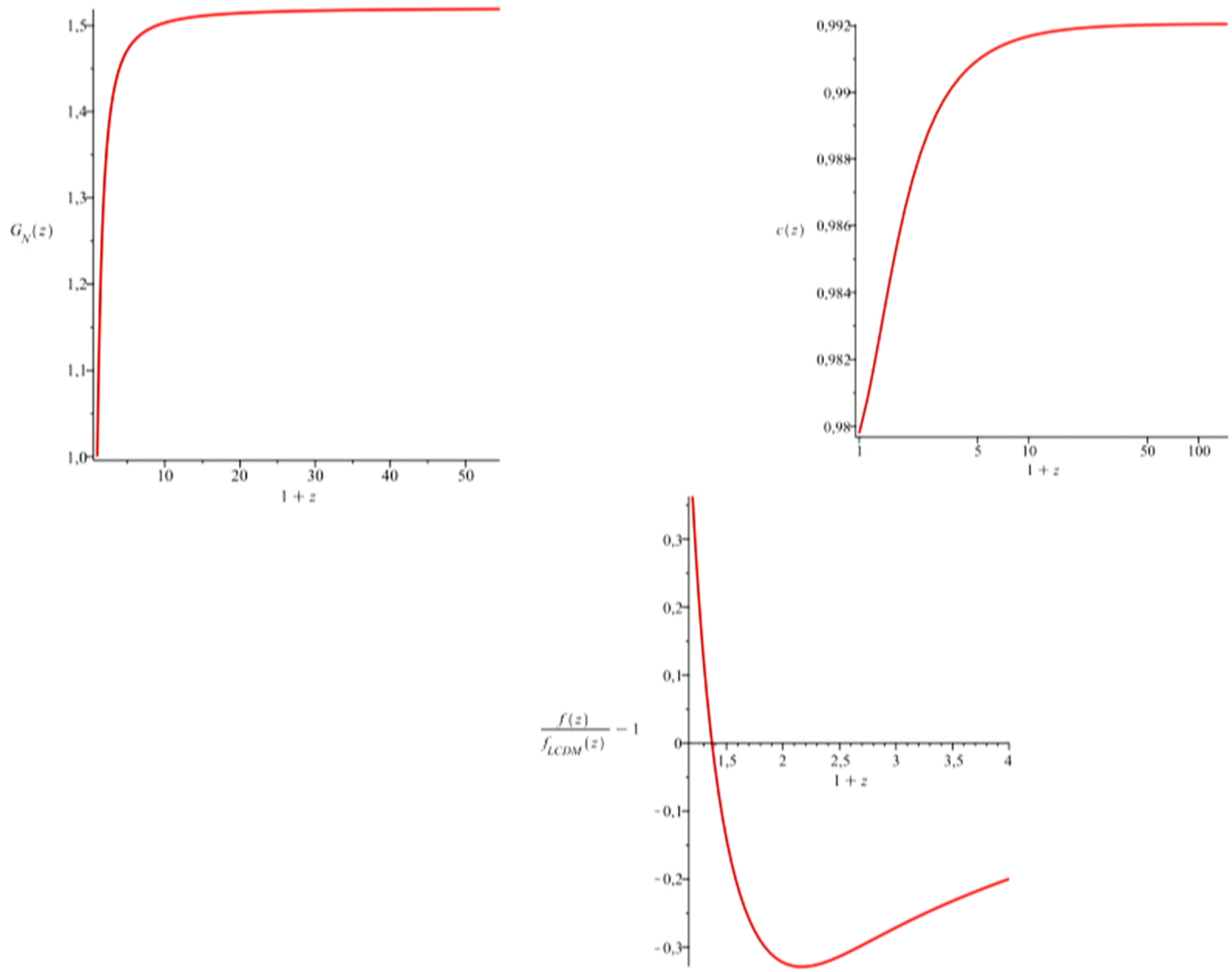

H(z)
500
100
50
10
5
1
0,5
1
5
10
50
100
1 + z


1 + z
2
4
6
8
10
12
14
16
18
20
ω
- 0,1
- 0,2
- 0,3
- 0,4
- 0,5
- 0,6
- 0,7
- 0,8
- 0,9
- 1



$G_N(z)$
1,0
1,1
1,2
1,3
1,4
1,5
10
20
30
40
50
1 + z
$c(z)$
0,98
0,982
0,984
0,986
0,988
0,99
0,992
1
5
10
50
100
1 + z
$\frac{f(z)}{f_{LCDM}(z)} - 1$
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
1,5
2
2,5
3
3,5
4
1 + z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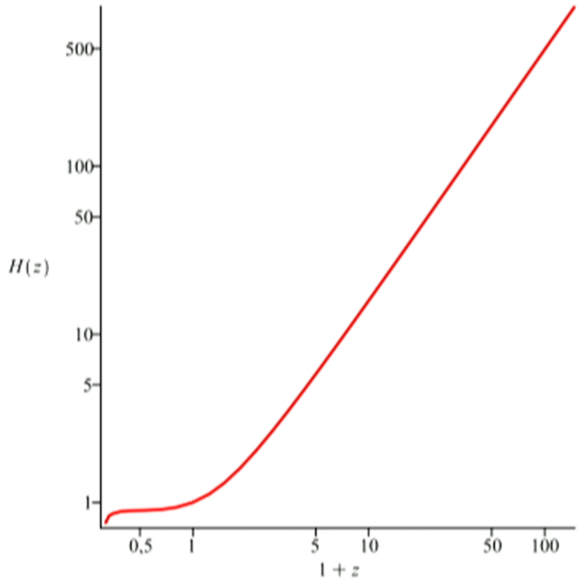
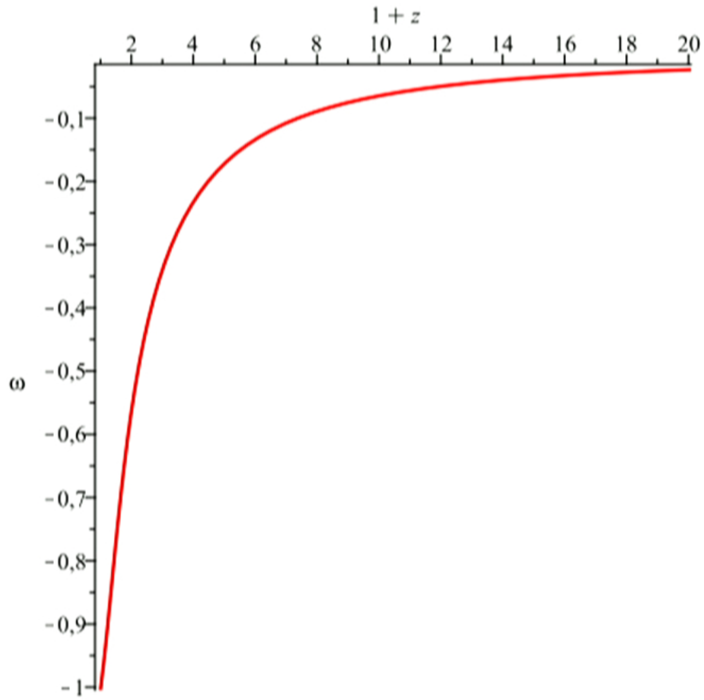
4
$1+z$


500
100
50
H(z)
10
5
1
0,5
1
5
10
50
100
1 + z


1 + z
2
4
6
8
10
12
14
16
18
20
ω
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
-1

There is an attractor solution. On the attractor we can constrain

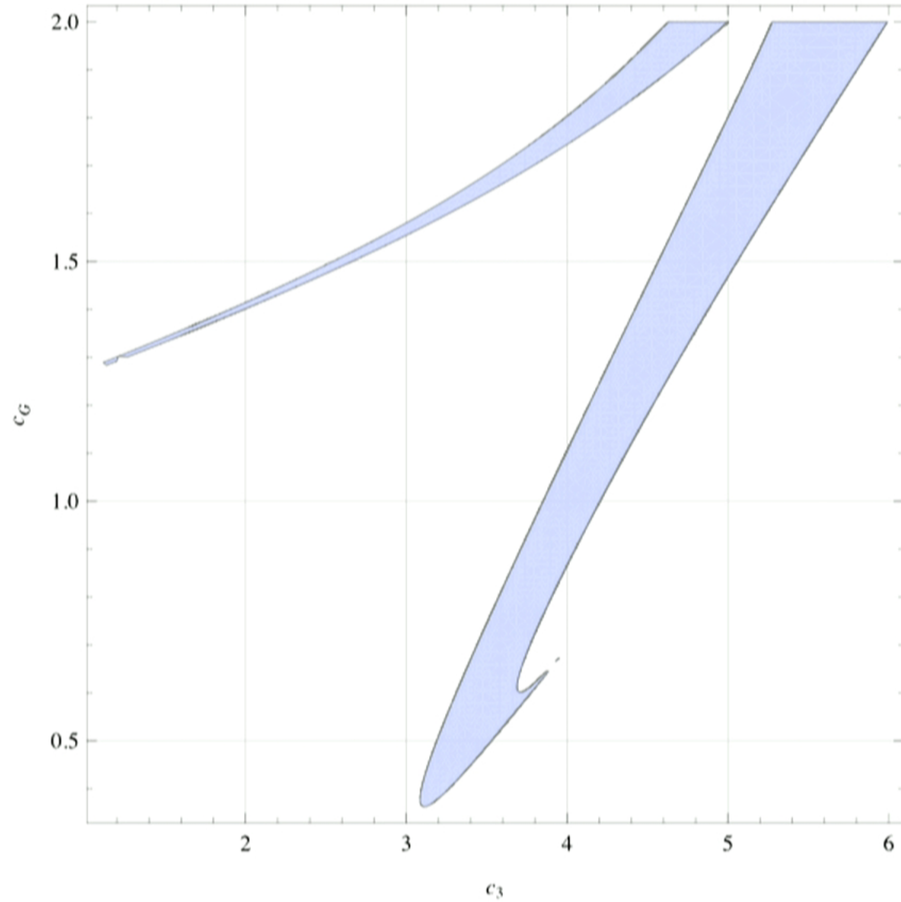
c_G and c_3

such that

$$g_{eff} < 0.2$$

on the attractor, given by the shaded region

Note the allowed parameter space is highly restricted



The Speed of Gravitons

An effect of Galileon theory is to change the speed of gravitons compared to that of light

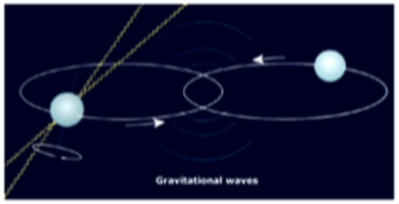
There are severe constraints

If $c_T < c$ relativisitic cosmic rays emit gravitons by Cerenkov radiation, suppressing them unless

$$1 - \frac{c_T}{c} \leq 10^{-17}$$

If $c_T > c$ then the period of binary pulsars would be affected unless

$$\frac{c_T}{c} - 1 \leq 10^{-2}$$



The speed of gravitons will be effected whenever the Einstein Hilbert term is changed in any way.

This occurs whenever $c_4 \neq 0$

Typically we are interested in the emission of spherical waves in a time-dependent cosmological background; the graviton wave equation takes the form

$$\omega^2(G_4 - G_{4,X}\dot{\phi}^2) - 2\omega k\dot{\phi}\partial_r\phi - k^2(G_4 + G_{4,X}(\partial_r\phi)^2) = 0$$

The speed of gravitational waves is screened when $G_{4,X} \approx 0$

when the effect would be Vainshtein screened

In this case

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

If $G_{4X} \approx 0$
then $c_T \approx 1$

We find that time derivatives are smaller than spatial derivatives when

$$R_V H_0 \gg 1$$

which is violated for around a solar mass,

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

and Vainshtein screening will not
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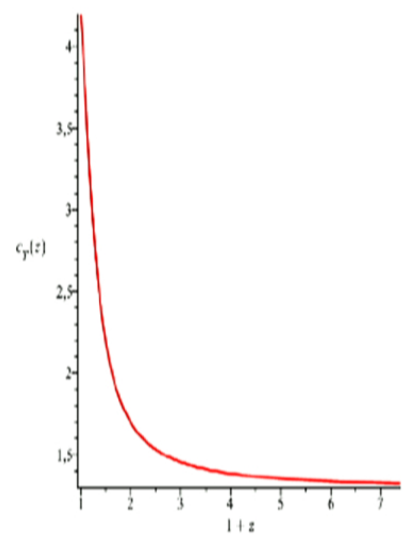
Subdominant Galileons

Consider the cubic galleon



$c_T^2 \sim 1 + 4c_4\Omega_m^2$

$c_4 \leq 4.10^{-2}$

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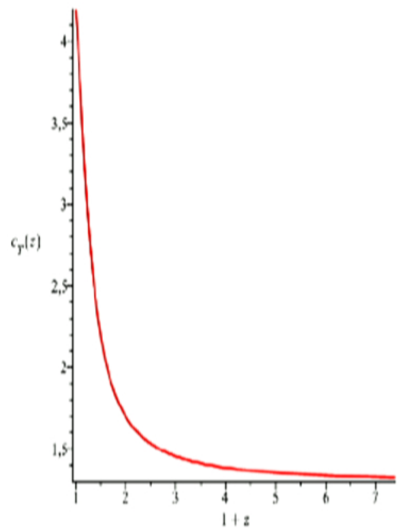

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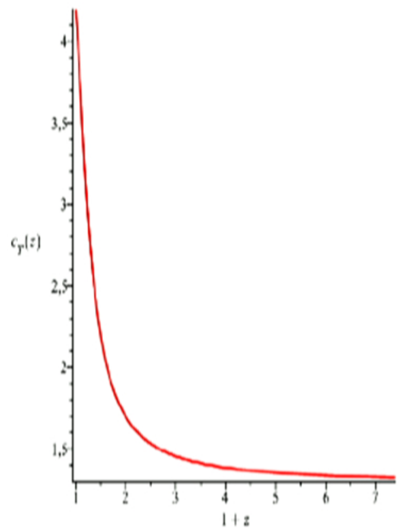

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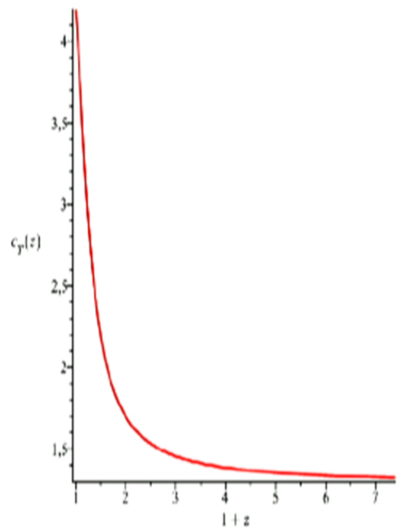

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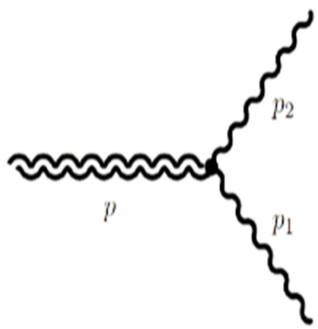
Can we really have gravity waves faster than the speed of light at the percent level?



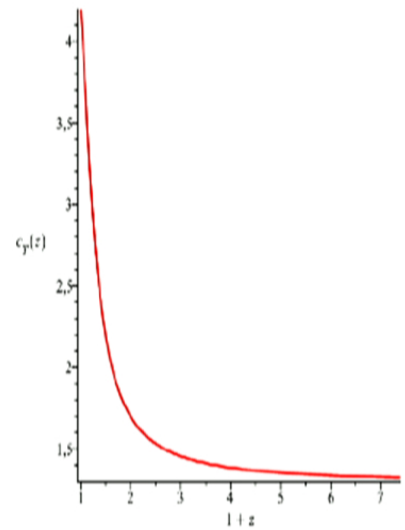
If gravitons go faster than the speed of light, they can decay into two photons.

For astrophysical sources, the decay time is much longer than the age of the Universe.

$$\Gamma \sim -\frac{(c_T^2 - 1)\ln(c_T - 1)}{16\pi}\frac{p^3}{m_{\rm Pl}^2}$$

Subdominant Galileons

Consider the cubic galleon



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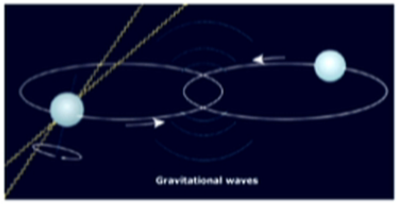

Time Delay a smoking gun?

Gravitons are expected to arrive before photons/neutrinos by

$$\frac{\Delta t}{t} = \Delta c_T$$

For supernova SN1987A the difference in emission times between neutrinos and gravitational waves is about 1/1000s. With bounds from binary pulsar for $\Delta c_T \approx 10^{-2}$ gives gravitational waves arriving 1700 years in advance, and for sources 1kpc away this is 30years!

If we detect both neutrinos and gravitons from a supernova 1kpc away with a time delay of 1/1000s this would constrain

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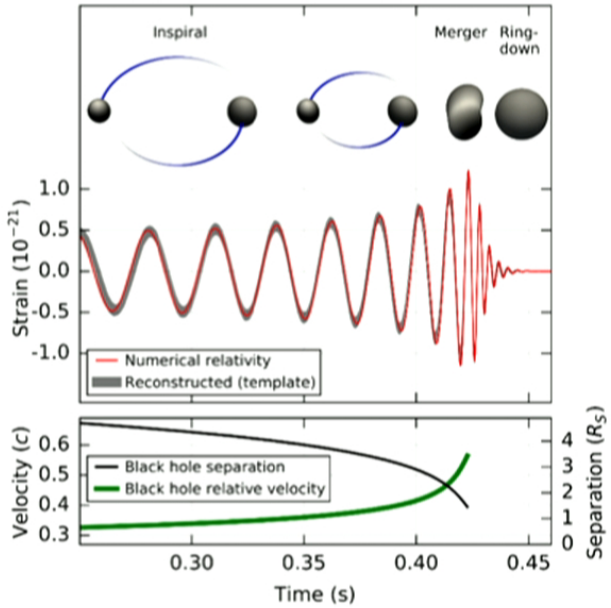
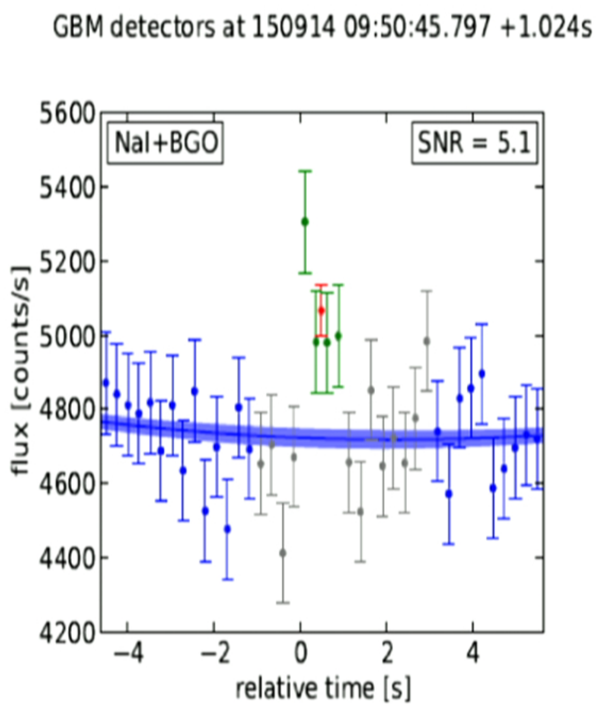
A tighter constraint?

The recent detection of gravitational waves does not give a bound on their speed.



If the gamma ray burst detected by the Fermi experiment is from the same source



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Cosmological galileons would be cubic and subdominant for the acceleration of the universe

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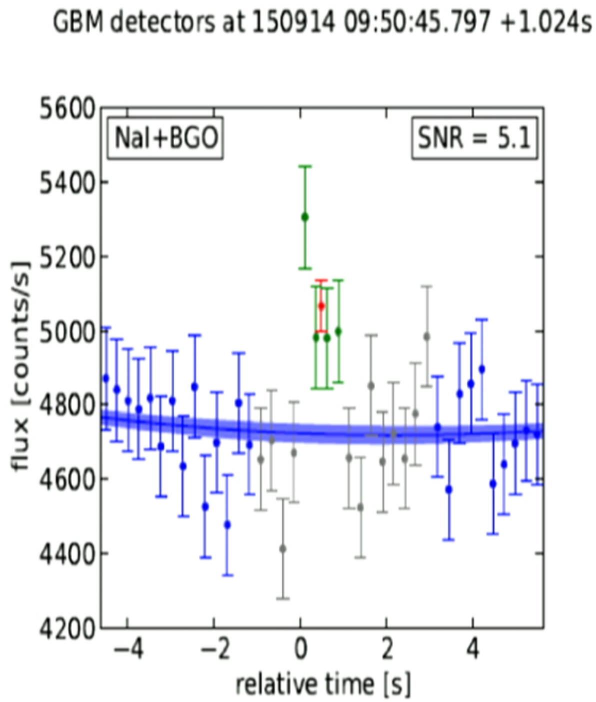

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Cosmological galileons would be cubic and subdominant for the acceleration of the universe

Shape Dependence

with Jolyon Bloomfield and Clare Burrage

Vainshtein screening usually considered for spherical symmetry. For both astrophysical bodies and for laboratory tests one needs to consider general symmetry

$$\mathcal{L} = -\frac{c_2}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{c_4}{\Lambda^6}\mathcal{L}_4 - \frac{c_5}{\Lambda^9}\mathcal{L}_5 + \sum_i \frac{c_0^i\phi}{m_{\rm Pl}}T_i - \sum_i \frac{c_G^i}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi T_i^{\mu\nu} ,$$

$$\begin{aligned}\mathcal{L}_4 =& (\partial\phi)^2\left[2(\Box\phi)^2 - 2D_\mu D_\nu\phi D^\nu D^\mu\phi - R\frac{(\partial\phi)^2}{2}\right]\\ \mathcal{L}_5 =& (\partial\phi)^2\left[(\Box\phi)^3 - 3(\Box\phi)D_\mu D_\nu\phi D^\nu D^\mu\phi + 2D_\mu D^\nu\phi D_\nu D^\rho\phi D_\rho D^\mu\phi\right.\\ &\left. -6D_\mu\phi D^\mu D^\nu\phi D^\rho\phi G_{\nu\rho}\right]\end{aligned}$$

Planar case we find

$$\phi = \begin{cases} \frac{\beta\rho_0}{2M_P} z^2 & |z| < z_0 \\ \frac{\beta\rho_0 z_0}{M_P}\left(z - \frac{z_0}{2}\right) & |z| \geq z_0 \end{cases}$$

$$\frac{F_\phi}{F_G} = 2\beta^2$$

The fifth force is unscreened

Cylindrical case gives

$$\frac{F_\phi}{F_G} = 4\beta^2 \frac{r}{r_v}$$

Note less screened than spherical case

Spherical case gives

$$r_v = \left(\frac{3}{4}\right)^{1/3} \left(\frac{2\beta M}{\pi M_P \Lambda^3}\right)^{1/3}$$

General Vainshtein Radius

$$\frac{F_\phi}{F_G} = 6\beta^2 \frac{r^2}{r_v^2}$$

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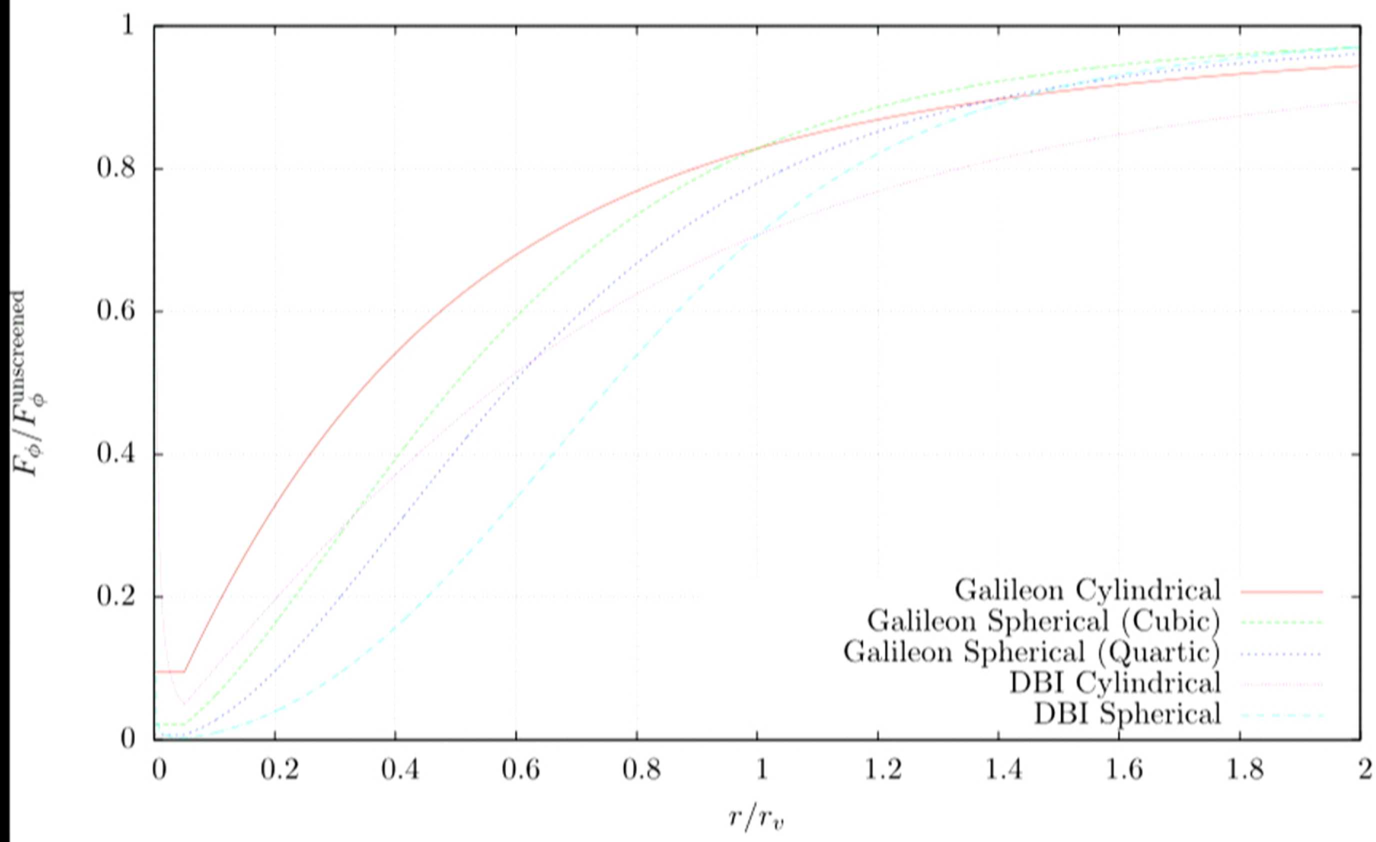

$F_\phi/F_\phi^{\rm unscreened}$
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
r/r_v
Galileon Cylindrical
Galileon Spherical (Cubic)
Galileon Spherical (Quartic)
DBI Cylindrical
DBI Spherical

What next?

Cosmological galileons with a Minkowski limit can't lead to the acceleration of the universe on their own since they lead to too large a deviation in the speed of gravitons compared to the speed of light.

If subdominant they can still lead to deviations which could be detectable eg in Casimir experiments like Cannex, or other lab experiments.

Astrophysically, what about planar objects being unscreened and cylindrical objects less screened?

Relax the requirement of Minkowski limit?

For me this is a no no

Galileon employs Vainshtein Screening and highly non-linear Lagrangian, but equations of motion only have second order time derivatives

$$\mathcal{L} = -\frac{c_2}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{c_4}{\Lambda^6}\mathcal{L}_4 - \frac{c_5}{\Lambda^9}\mathcal{L}_5 + \sum_i \frac{c_0^i\phi}{m_{\rm Pl}}T_i - \sum_i \frac{c_G^i}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi T_i^{\mu\nu} ,$$

where c_0 and c_G are the conformal and disformal couplings

we take $\Lambda^3 = H_0^2 m_{\rm Pl}$ to be of cosmological interest

and $c_2 > 0$ to avoid ghosts in Minkowski space

The coupling to the metric is $\tilde{g}^i_{\mu\nu} = A^i(\phi)g_{\mu\nu} + \frac{2}{M_i^4}\partial_\mu\phi\partial_\nu\phi$. with $A^i(\phi) = 1 + \frac{c_0^i\phi}{m_{\rm Pl}}$

$$\mathcal{L}_4 =(\partial\phi)^2\left[2(\Box\phi)^2 - 2D_\mu D_\nu\phi D^\nu D^\mu\phi - R\frac{(\partial\phi)^2}{2}\right]$$

$$\mathcal{L}_5 =(\partial\phi)^2\left[(\Box\phi)^3 - 3(\Box\phi)D_\mu D_\nu\phi D^\nu D^\mu\phi + 2D_\mu D^\nu\phi D_\nu D^\rho\phi D_\rho D^\mu\phi - 6D_\mu\phi D^\mu D^\nu\phi D^\rho\phi G_{\nu\rho}\right]$$

these are the remaining terms and play a role cosmologially