Can quantum vacuum be the physical origin of Acceleration?

Alain Blanchard

Arnaud Dupays (LCAR), Brahim Lamine (LKB)

Chania "Recent developments in Gravity", June 26, 2012

Acceleration from SNIa Hubble diagram

SNIa are bright objects that can be detected are large distances.

Up to $z \sim 2$ i.e. $t(z) \sim 3$ Gyr

SNIa are "standardizable".

Acceleration from SNIa Hubble diagram

SNIa are bright objects that can be detected are large distances.

Up to $z \sim 2$ i.e. $t(z) \sim 3$ Gyr

SNIa are "standardizable".

Acceleration from SNIa Hubble diagram

SNIa are bright objects that can be detected are large distances.

Up to $z \sim 2$ i.e. $t(z) \sim 3$ Gyr

SNIa are "standardizable".

Distant SNIa

Just look for distant supernovae...

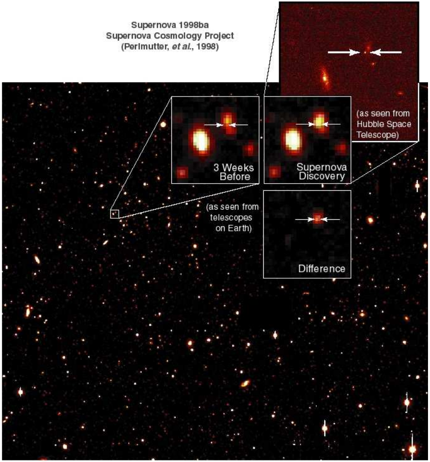
Distant SNIa

Just look for distant supernovae...
One SNIa/galaxy/century

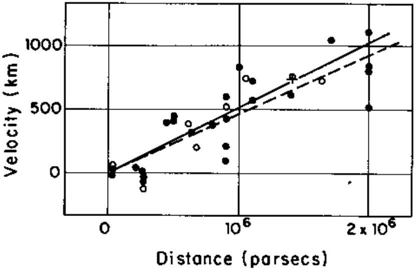
Distant SNIa

Just look for distant supernovae...
One SNIa/galaxy/century

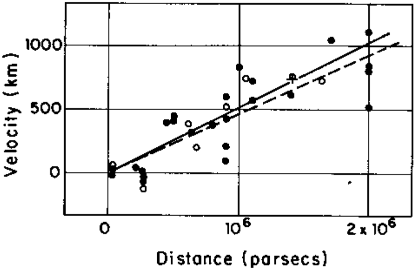
Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

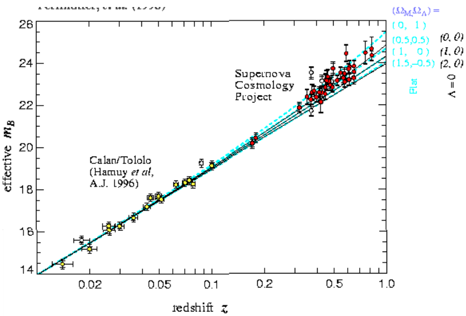


SNIa Hubble diagramm



SNIa Hubble diagramm





Acceleration!!

Nobel Prize in Physics 2011

Nobel Prize in Physics 2011

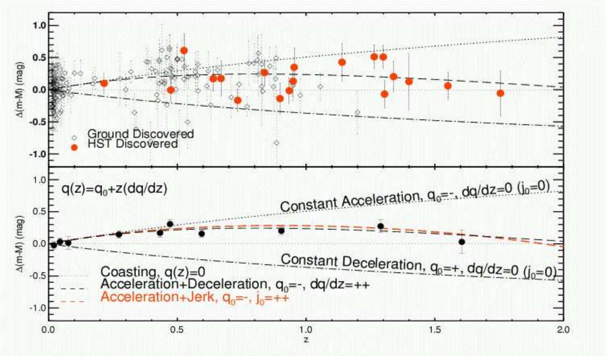
S.Perlmuter, A.Riess, B.Schmidt

Distant SNIa Hubble diagramm

$$\ddot{R} \propto -(\rho_m(1+z)^3 - 2\rho_\Lambda)R$$

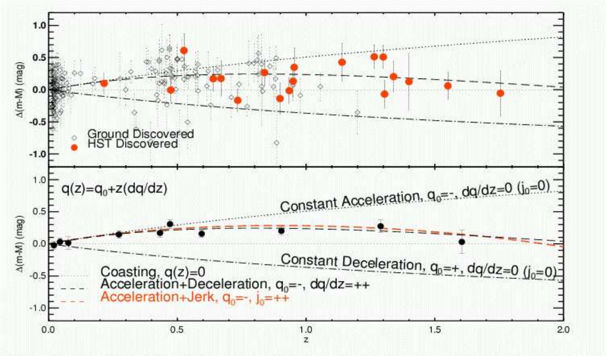
Distant SNIa Hubble diagramm

$$\ddot{R} \propto -(\rho_m(1+z)^3 - 2\rho_\Lambda)R$$



Distant SNIa Hubble diagramm

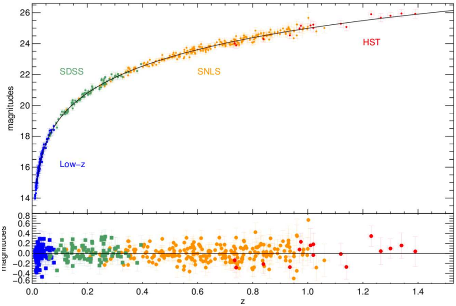
$$\ddot{R} \propto -(\rho_m(1+z)^3 - 2\rho_\Lambda)R$$



→ Acceleration+decceleration!!

SNIa Hubble diagramm (2012)

SNLS



What if SNIa evolved ?

What if SNIa evolved ?

$$\Delta m(z) = K\left(\frac{t_0 - t(z)}{t_0 - t_1}\right)$$

What if SNIa evolved ?

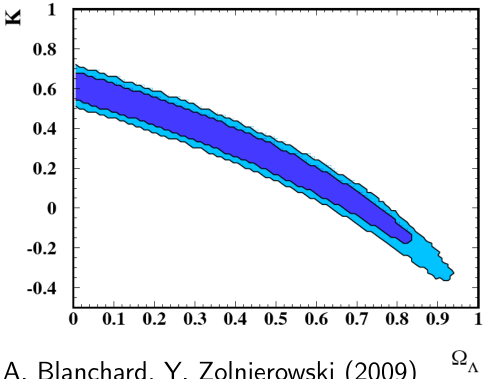
$$\Delta m(z) = K\left(\frac{t_0 - t(z)}{t_0 - t_1}\right)$$

Fit the Hubble diagramm with K and Λ

What if SNIa evolved ?

$$\Delta m(z) = K\left(\frac{t_0 - t(z)}{t_0 - t_1}\right)$$

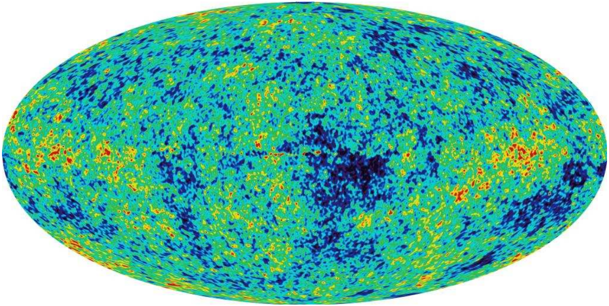
Fit the Hubble diagramm with K and Λ



L. Ferramacho, A. Blanchard, Y. Zolnierowski (2009)

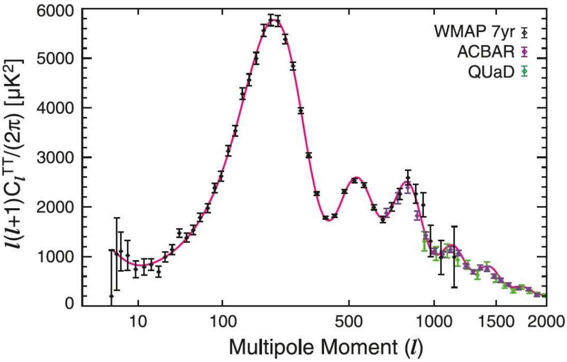
Cosmic microwave radiation fluctuations

Cosmic microwave radiation fluctuations



WMAP 1, 3, 5, 7,...

Cosmic microwave radiation fluctuations



Cosmic microwave radiation fluctuations

Essentially geometric:

$z_{lss} \approx 1090$

Angular distance to the CMB is the key parameter, combined with the accoustic scale r_S corresponding to the sound horizon at ls:

$$l_A = \frac{D_{ang}(z_{lss})}{r_S}$$

The shift parameter:

$$R = \sqrt{\Omega_m H_0^2} D_{ang}(z_{lss}) = 1.710 \pm 0.019$$

Cosmic microwave radiation fluctuations

Essentially geometric:

$z_{lss} \approx 1090$

Angular distance to the CMB is the key parameter, combined with the accoustic scale r_S corresponding to the sound horizon at *ls*:

$$l_A = \frac{D_{ang}(z_{lss})}{r_S}$$

The shift parameter:

$$R = \sqrt{\Omega_m H_0^2} D_{ang}(z_{lss}) = 1.710 \pm 0.019$$

Cosmic microwave radiation fluctuations

Essentially geometric:

$z_{lss} \approx 1090$

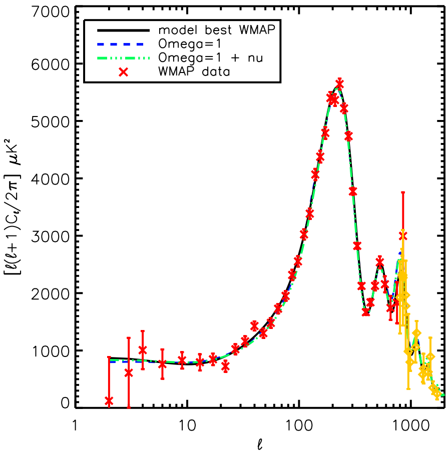
Angular distance to the CMB is the key parameter, combined with the accoustic scale r_S corresponding to the sound horizon at ls:

$$l_A = \frac{D_{ang}(z_{lss})}{r_S}$$

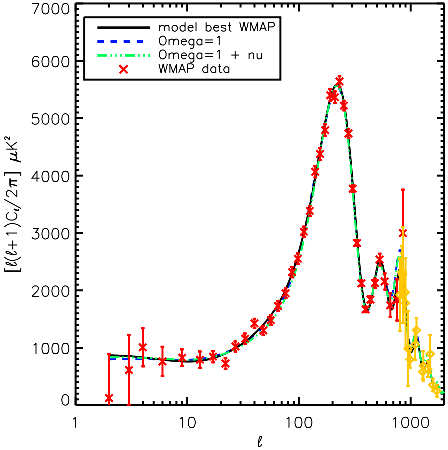
The shift parameter:

$$R = \sqrt{\Omega_m H_0^2} D_{ang}(z_{lss}) = 1.710 \pm 0.019$$

Cosmic microwave radiation fluctuations



Cosmic microwave radiation fluctuations



Degeneracy in parameters allows to reproduce the C_l

Blanchard et al., 2003

Conlusion (at this point)

Conlusion (at this point)

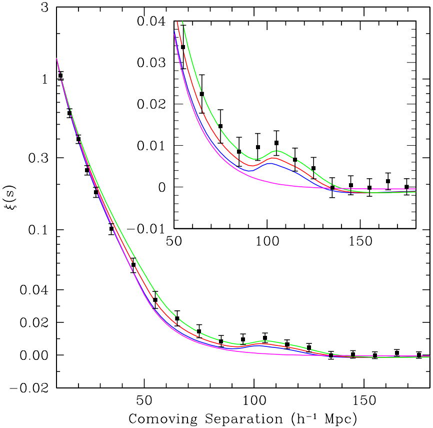
Neither SNIa nor CMB strongly require acceleration!

But...

The sound horizon is also imprinted in the matter distribution:

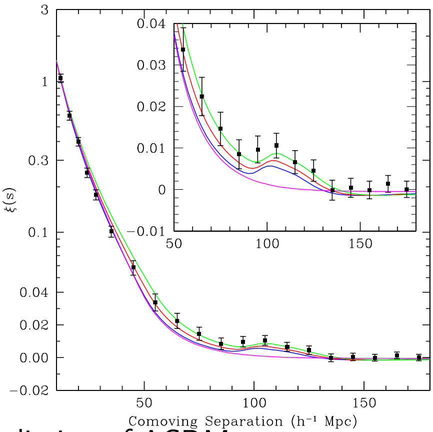
But...

The sound horizon is also imprinted in the matter distribution:



But...

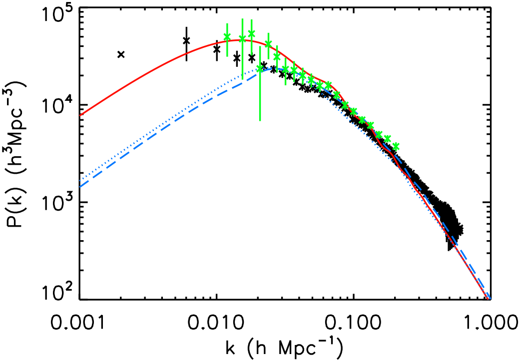
The sound horizon is also imprinted in the matter distribution:



This was a prediction of ΛCDM

(Very) Positive point for ΛCDM

(Very) Positive point for ΛCDM



Standard Cosmological model: ΛCDM

Parameters in ΛCDM

Standard Cosmological model: ΛCDM

Parameters in ΛCDM

...pretty well estimated

Standard Cosmological model: ΛCDM

Parameters in ΛCDM

...pretty well estimated

SNIa,

Standard Cosmological model: ΛCDM

Parameters in ΛCDM

...pretty well estimated

SNIa, CMB,

Standard Cosmological model: ΛCDM

Parameters in ΛCDM

...pretty well estimated

SNIa, CMB, P(k)

Standard Cosmological model: ΛCDM

Parameters in ΛCDM

...pretty well estimated

SNIa, CMB, P(k)

Parameter	Vanilla	Vanilla + Ω_k	Vanilla + w	Vanilla + Ω_k + w
$\Omega_b h^2$	0.0227 ± 0.0005	0.0227 ± 0.0006	0.0228 ± 0.0006	0.0227 ± 0.0005
$\Omega_c h^2$	0.112 ± 0.003	0.109 ± 0.005	0.109 ± 0.005	0.109 ± 0.005
θ	1.042 ± 0.003	1.042 ± 0.003	1.042 ± 0.003	1.042 ± 0.003
τ	0.085 ± 0.017	0.088 ± 0.017	0.087 ± 0.017	0.088 ± 0.017
n_s	0.963 ± 0.012	0.964 ± 0.013	0.967 ± 0.014	0.964 ± 0.014
$log(10^{10} A_s)$	3.07 ± 0.04	3.06 ± 0.04	3.06 ± 0.04	3.06 ± 0.04
Ω_k	0	-0.005 ± 0.007	0	-0.005 ± 0.0121
w	-1	-1	-0.965 ± 0.056	-1.003 ± 0.102
Ω_Λ	0.738 ± 0.015	0.735 ± 0.016	0.739 ± 0.014	0.733 ± 0.020
Age	13.7 ± 0.1	13.9 ± 0.4	13.7 ± 0.1	13.9 ± 0.6
Ω_m	0.262 ± 0.015	0.270 ± 0.019	0.261 ± 0.020	0.272 ± 0.029
σ_8	0.806 ± 0.023	0.791 ± 0.030	0.816 ± 0.014	0.788 ± 0.042
z_{re}	10.9 ± 1.4	11.0 ± 1.5	11.0 ± 1.5	11.0 ± 1.4
h	0.716 ± 0.014	0.699 ± 0.028	0.713 ± 0.015	0.698 ± 0.037

L. Ferramacho, A. Blanchard, Y. Zolnierowski (2009)

What does it mean?

What does it mean?

What does it mean?

In GR, the source of gravity is ρ and P:

$$\ddot{R} \propto -(\rho + 3P)R$$

What does it mean?

In GR, the source of gravity is ρ and P:

$$\ddot{R} \propto -(\rho + 3P)R$$

Observations need $P \approx -\rho$

What does it mean?

In GR, the source of gravity is ρ and P:

$$\ddot{R} \propto -(\rho + 3P)R$$

Observations need $P \approx -\rho$
So that the gravity strength is repulsive and proportional to R

...

Historical aspects

Λ was introduced by Einstein

Historical aspects

Λ was introduced by Einstein

Nerst (1916) and Pauli discussed the possible contribution of zero-point energy to the density of the Universe ($\rightarrow$ Kragh

`arXiv:1111.4623`)

Historical aspects

Λ was introduced by Einstein

Nerst (1916) and Pauli discussed the possible contribution of zero-point energy to the density of the Universe ($\rightarrow$ Kragh

arXiv:1111.4623)
Lemaître (1934) made the comment that Λ is equivalent to a Lorentz invariant non-zero vacuum, i.e.

$$p = -\rho$$

Historical aspects

Λ was introduced by Einstein

Nerst (1916) and Pauli discussed the possible contribution of zero-point energy to the density of the Universe ($\rightarrow$ Kragh

`arXiv:1111.4623`)
Lemaître (1934) made the comment that Λ is equivalent to a Lorentz invariant non-zero vacuum, i.e.

$$p = -\rho$$

So is this the origin of the acceleration ?

Historical aspects

No!

Historical aspects

No!

The Vacuum catastroph (Weinberg, 1989):

$$\rho_v = \langle 0| T^{00} |0\rangle = \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

highly divergent.

Historical aspects

No!

The Vacuum catastroph (Weinberg, 1989):

$$\rho_v = \langle 0 | T^{00} | 0 \rangle = \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

highly divergent :

$$\rho_v(k_c) \propto \frac{k_c^4}{16\pi^2}$$

Equation of state

The pressure:

$$p_v = (\mathbf{1}/\mathbf{3}) \sum_i \langle 0 | T^{ii} | 0 \rangle = \frac{1}{3} \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

Equation of state

The pressure:

$$p_v = (\mathbf{1}/\mathbf{3}) \sum_i \langle 0 | T^{ii} | 0 \rangle = \frac{1}{3} \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

So that any regularization that is applied to both quantities leads to the e.o.s.:

Equation of state

The pressure:

$$p_v = (\mathbf{1}/\mathbf{3}) \sum_i \langle 0 | T^{ii} | 0 \rangle = \frac{1}{3} \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

So that any regularization that is applied to both quantities leads to the e.o.s.:

$$p = \frac{1}{3}\rho$$

Equation of state

The pressure:

$$p_v = (\mathbf{1/3}) \sum_i \langle 0 | T^{ii} | 0 \rangle = \frac{1}{3} \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

So that any regularization that is applied to both quantities leads to the e.o.s.:

$$p = \frac{1}{3}\rho$$

i.e. eq. (1) + eq. (2) leads to :

$$p_v = \rho_v = 0$$

Equation of state

The pressure:

$$p_v = (\mathbf{1/3}) \sum_i \langle 0 | T^{ii} | 0 \rangle = \frac{1}{3} \frac{1}{2(2\pi)^3} \int_0^{+\infty} k \, \mathrm{d}^3\mathbf{k}$$

So that any regularization that is applied to both quantities leads to the e.o.s.:

$$p = \frac{1}{3}\rho$$

i.e. eq. (1) + eq. (2) leads to :

$$p_v = \rho_v = 0$$

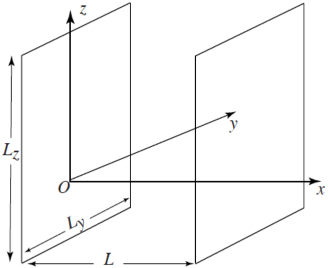
→ usual conclusion on zero-point energy contribution.
(does not hold for a massive field cf J.Martin 2012)

Casimir effect

Where is there vacuum contribution in laboratory physics?

Casimir effect

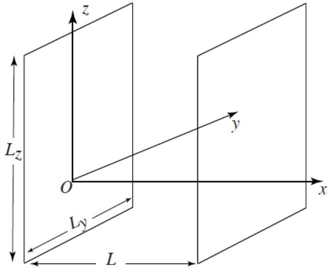
Where is there vacuum contribution in laboratory physics?



Casimir effect

Casimir effect

Where is there vacuum contribution in laboratory physics?



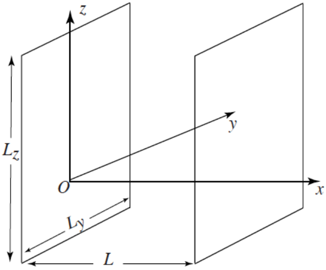
Casimir effect

with:

$$p_x = 3\rho$$

Casimir effect

Where is there vacuum contribution in laboratory physics?



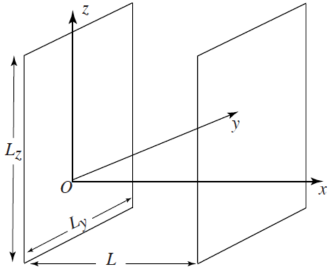
Casimir effect

with:

$$p_x = 3\rho < 0$$

Casimir effect

Where is there vacuum contribution in laboratory physics?



Casimir effect

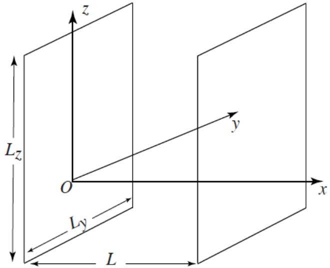
with:

$$p_x = 3\rho < 0$$

and ...

Casimir effect

Where is there vacuum contribution in laboratory physics?



Casimir effect

with:

$$p_x = 3\rho < 0$$

and ...

$$p_{//} = -\rho$$

Brown & Maclay (1968)

Casimir effect from higher dimension

Assume there is an additional compact dimension.

Casimir effect from higher dimension

Assume there is an additional compact dimension.

The quantification of gravitational field modes in the bulk leads to a Casimir energy (Appelquist & Chodos, 1983).

Casimir effect from higher dimension

Assume there is an additional compact dimension.

The quantification of gravitational field modes in the bulk leads to a Casimir energy (Appelquist & Chodos, 1983).
This result can be established by evaluating zero mode contributions (Rohrlich 1984).

Casimir effect from higher dimension

Assume there is an additional compact dimension.

The quantification of gravitational field modes in the bulk leads to a Casimir energy (Appelquist & Chodos, 1983).
This result can be established by evaluating zero mode contributions (Rohrlich 1984). Dispersion relation:

$$\omega^2 = k^2 + \frac{n^2}{R^2}$$

Casimir effect from higher dimension

Assume there is an additional compact dimension.

The quantification of gravitational field modes in the bulk leads to a Casimir energy (Appelquist & Chodos, 1983).
This result can be established by evaluating zero mode contributions (Rohrlich 1984). Dispersion relation:

$$\omega^2 = k^2 + \frac{n^2}{R^2}$$

At high energy, only modes with λ smaller than ct have to be taken into account i.e.:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_{\omega>\omega_H}^{\infty} k^2 \mathrm{d}k \left[\sum_{n=-\infty}^{\infty} \left(k^2 + \frac{n^2}{R^2} \right)^{1/2} \right]$$

Casimir effect: the horizon

At high energy, only modes with λ smaller than ct have to be taken into account i.e.:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_0^\infty k^2 \mathrm{d}k \, [...] - \frac{5\hbar c}{8\pi^3 R} \int_0^{\omega_H} k^2 \mathrm{d}k \, [...]$$

Casimir effect: the horizon

At high energy, only modes with λ smaller than ct have to be taken into account i.e.:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R}\int_0^{\infty} k^2 \mathrm{d}k\,[...] - \frac{5\hbar c}{8\pi^3 R}\int_0^{\omega_H} k^2 \mathrm{d}k\,[...]$$

However, as long as $ct \ll 2\pi R$ vacuum should be that of a massless field in a 4+1D space time i.e.:

$$\rho_v = 0$$

Isotropy ends...

when $\omega_H \sim \frac{1}{R}$, this is the last time at which symetries ensure $\rho_v = 0$. Then

$$\rho_v = \frac{5\hbar c}{8\pi^3 R}\int_0^{\infty} k^2 \mathrm{d}k\,[...] - \frac{5\hbar c}{8\pi^3 R}\int_0^{1/R} k^2 \mathrm{d}k\,[...] = 0$$

Isotropy ends...

when $\omega_H \sim \frac{1}{R}$, this is the last time at which symetries ensure $\rho_v = 0$. Then

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_0^\infty k^2 \mathrm{d}k \,[...] - \frac{5\hbar c}{8\pi^3 R} \int_0^{1/R} k^2 \mathrm{d}k \,[...] = 0$$

Later, when $ct \gg 2\pi R$ i.e. $\omega_H \sim 0$

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_0^\infty k^2 \mathrm{d}k \,[...] = \frac{5\hbar c}{8\pi^3 R} \int_0^{1/R} k^2 \mathrm{d}k \,[...]$$

with :

$$[...] = \left[\sum_{n=-\infty}^{\infty} \left(k^2 + \frac{n^2}{R^2} \right)^{1/2} \right]$$

Isotropy ends...

The condition :

$$\omega = \sqrt{k^2 + \frac{n^2}{R^2}} < \frac{1}{R}$$

ensured only if $n = 0$, so:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_0^{1/R} k^3 \mathrm{d}k = \frac{5\hbar c}{32\pi^3 R^5}$$

Isotropy ends...

The condition :

$$\omega = \sqrt{k^2 + \frac{n^2}{R^2}} < \frac{1}{R}$$

ensured only if $n = 0$, so:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R} \int_0^{1/R} k^3 \mathrm{d}k = \frac{5\hbar c}{32\pi^3 R^5}$$

In the brane:

$$\rho_v = \frac{5\hbar c}{16\pi^2 R^4}$$

Isotropy ends...

The condition :

$$\omega = \sqrt{k^2 + \frac{n^2}{R^2}} < \frac{1}{R}$$

ensured only if $n = 0$, so:

$$\rho_v = \frac{5\hbar c}{8\pi^3 R}\int_0^{1/R} k^3 \mathrm{d}k = \frac{5\hbar c}{32\pi^3 R^5}$$

In the brane:

$$\rho_v = \frac{5\hbar c}{16\pi^2 R^4}$$

$R \sim 25\mu\mathrm{m}$ fits data. Corresponding to $E \sim 1\,TeV$

Conclusion

Casimir effect from quantized massless field in additional compact dimension can produce a non-zero vacuum contribution to the density of the universe with the correct equation of state for a cosmological constant.

Conclusion

Casimir effect from quantized massless field in additional compact dimension can produce a non-zero vacuum contribution to the density of the universe with the correct equation of state for a cosmological constant.

With $R \sim 25\mu\text{m}$ it produces a cosmological constant as observed.$\rightarrow$ gravitation is modified on scales $\leq 25\mu\text{m}$

Conclusion

Casimir effect from quantized massless field in additional compact dimension can produce a non-zero vacuum contribution to the density of the universe with the correct equation of state for a cosmological constant.

With $R \sim 25\mu\mathrm{m}$ it produces a cosmological constant as observed.$\rightarrow$ gravitation is modified on scales $\leq 25\mu\mathrm{m}$

Acceleration could be the direct manifestation of the quantum gravitational vacuum: $w = -1$