# Dynamical vacuum and the variation of the Newtonian coupling G

Adrià Gómez Valent
PhD student under the supervision of

Prof. Joan Solà


INSTITUTE OF COSMOS SCIENCES
University of Barcelona


CPAN days Segovia, 1st december 2015

# Outline

- Existing conundrums associated to the cosmological constant
- Evidence in favour of the non-rigidity of $\Lambda$
- β-function for $\Lambda$
- Possible implications of a variable cosmological term
- $\Lambda_t G_t$CDM model:

a. Background solutions
b. Linear structure formation
c. Fitting analysis

- Main results
- Brief summary

# Existing problems

# Existing problems

- How can theory explain the observed tiny value of the CC?

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$

II. Electroweak vacuum $$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\rho_\Lambda^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$

II. Electroweak vacuum $$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

QFT contributions

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_\Lambda^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$

II. Electroweak vacuum $$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

} QFT contributions

III. Pure geometrical term in the lhs of Einstein's equations

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\longrightarrow \quad \rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2} \approx \frac{k_{max}^4}{16\pi^2}$$

II. Electroweak vacuum $$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

**Fine tuning is needed!**

# Existing problems

- How can theory explain the observed tiny value of the CC?

$$\rho_{\Lambda}^{(0)} \sim 10^{-47} GeV^4$$

Several contributions to the this energy density:

I. Zero-point energy $$\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2}$$

II. Electroweak vacuum $$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

**Fine tuning is needed!**

**OLD COSMOLOGICAL CONSTANT PROBLEM**

# Existing problems

- Why is the current value of the matter energy density of the same order of the vacuum energy density?

$$\frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}} \sim \mathcal{O}(1)$$

# Existing problems

- Why is the current value of the matter energy density of the same order of the vacuum energy density?

$$\frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}} \sim \mathcal{O}(1)$$

$$\frac{\rho_m(z)}{\rho_\Lambda(z)} = \frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}}(1+z)^3$$

# Existing problems

- Why is the current value of the matter energy density of the same order of the vacuum energy density?

$$\frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}} \sim \mathcal{O}(1)$$

$$\frac{\rho_m(z)}{\rho_\Lambda(z)} = \frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}}(1+z)^3 \longrightarrow$$

Density equality at z≈0.33, when the Universe was ≈10 Gyrs old, almost 4 Gyrs ago, not precisely today!

# Existing problems

- Why is the current value of the matter energy density of the same order of the vacuum energy density?

$$\frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}} \sim \mathcal{O}(1)$$

$$\frac{\rho_m(z)}{\rho_\Lambda(z)} = \frac{\Omega_m^{(0)}}{\Omega_\Lambda^{(0)}}(1+z)^3 \longrightarrow$$

Density equality at z≈0.33, when the Universe was ≈10 Gyrs old, almost 4 Gyrs ago, not precisely today!

Is the coincidence problem really a problem?

# MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic: $$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

# MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic: $$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

- In the LCDM: $$H^2(z) = H_0^2 \left(1 + \Omega_m^{(0)}[(1+z)^3 - 1]\right) \longrightarrow Omh^2_\Lambda = \Omega_m^{(0)} \left(\frac{H_0}{100}\right)^2$$

# MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic: $$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

- In the LCDM: $$H^2(z) = H_0^2 \left(1 + \Omega_m^{(0)}[(1+z)^3 - 1]\right) \longrightarrow Omh^2_\Lambda = \Omega_m^{(0)} \left(\frac{H_0}{100}\right)^2$$

Planck 2015

$\mathrm{Omh^2} = \Omega_m h^2 = 0.1415 \pm 0.0019$

Using the available Hubble function data set

$\mathrm{Omh^2} = 0.1250 \pm 0.0039$

# MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic: $$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

- In the LCDM: $$H^2(z) = H_0^2 \left(1 + \Omega_m^{(0)}[(1+z)^3 - 1]\right) \longrightarrow Omh^2_\Lambda = \Omega_m^{(0)} \left(\frac{H_0}{100}\right)^2$$

Planck 2015

$$\mathrm{Omh^2} = \Omega_m h^2 = 0.1415 \pm 0.0019$$

$\neq$

Using the available Hubble function data set

$$\mathrm{Omh^2} = 0.1250 \pm 0.0039$$

# MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic: $$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

- In the LCDM: $$H^2(z) = H_0^2 \left(1 + \Omega_m^{(0)}[(1+z)^3 - 1]\right) \longrightarrow Omh^2_\Lambda = \Omega_m^{(0)} \left(\frac{H_0}{100}\right)^2$$

Planck 2015

$$\mathrm{Omh^2} = \Omega_m h^2 = 0.1415 \pm 0.0019$$

Using the available Hubble function data set

$$\mathrm{Omh^2} = 0.1250 \pm 0.0039$$

$\neq$

**Probably, Λ must be dynamical**

# β function for Λ

Renormalization Group Equation:

$$\frac{d\Lambda(\mu)}{d\,ln\mu} = \frac{1}{(4\pi)^2}\left[\sum_i C_i\mu^2 + \sum_i D_i\frac{\mu^4}{M_i^2} + ...\right]$$

# β function for Λ

**Some References:**

*I.L. Shapiro & J. Solà, JHEP 0202 (2002) 006*
*J. Solà, J.Phys. A41 (2008) 164066*
*I.L. Shapiro & J. Solà, Phys.Lett. B682 (2009) 105-113*
*J. Solà, J.Phys.Conf.Ser. 453 (2013) 012015*

Renormalization Group Equation:

$$\frac{d\Lambda(\mu)}{d\,ln\mu} = \frac{1}{(4\pi)^2}\left[\sum_i C_i\mu^2 + \sum_i D_i\frac{\mu^4}{M_i^2} + ...\right]$$

# β function for Λ

**Some References:**

*I.L. Shapiro & J. Solà, JHEP 0202 (2002) 006*
*J. Solà, J.Phys. A41 (2008) 164066*
*I.L. Shapiro & J. Solà, Phys.Lett. B682 (2009) 105-113*
*J. Solà, J.Phys.Conf.Ser. 453 (2013) 012015*

Renormalization Group Equation:

$$\frac{d\Lambda(\mu)}{d\,ln\mu} = \frac{1}{(4\pi)^2}\left[\sum_i C_i\mu^2 + \sum_i D_i\frac{\mu^4}{M_i^2} + ...\right]$$

After identifying μ with the Hubble function and integrating we find:

$$\Lambda(t) = c_0 + \sum_{k=1}\alpha_k H^{2k}(t) + \sum_{k=1}\beta_k\dot{H}(t)$$

# β function for Λ

**Some References:**

*I.L. Shapiro & J. Solà, JHEP 0202 (2002) 006*
*J. Solà, J.Phys. A41 (2008) 164066*
*I.L. Shapiro & J. Solà, Phys.Lett. B682 (2009) 105-113*
*J. Solà, J.Phys.Conf.Ser. 453 (2013) 012015*

Renormalization Group Equation:

$$\frac{d\Lambda(\mu)}{d\,ln\mu} = \frac{1}{(4\pi)^2}\left[\sum_i C_i\mu^2 + \sum_i D_i\frac{\mu^4}{M_i^2} + ...\right]$$

After identifying μ with the Hubble function and integrating we find:

LOW-ENERGY LIMIT $\Lambda(H) = C_0 + C_H H^2 + C_{\dot{H}}\dot{H}$

# Possible consequences of the variation of Λ

Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$

↓ Einstein's equations

$\nabla^\mu (G\, T_{\mu\nu}) = 0$ Covariant conservation laws

↓ For ν=0

$$\frac{d}{dt}\left[G(\rho_m + \rho_\Lambda)\right] + 3\,G\,H\,(\rho_m + p_m) = 0$$

# Possible consequences of the variation of Λ

**I: G is constant and matter exchanges energy with the vacuum.**

- Gómez-Valent A., Solà J. & Basilakos S., 2015, J. Cosmol. Astropart. Phys. 0402, 006
- Gómez-Valent A. & Solà J.,2015, Mont. Not. Roy. Astron. Soc. 448, 2810-2821

$$\dot{\rho}_\Lambda + \dot{\rho}_m + 3H\rho_m = 0$$

# Possible consequences of the variation of Λ

**I: G is constant and matter exchanges energy with the vacuum.**

- Gómez-Valent A., Solà J. & Basilakos S., 2015, J. Cosmol. Astropart. Phys. 0402, 006
- Gómez-Valent A. & Solà J.,2015, Mont. Not. Roy. Astron. Soc. 448, 2810-2821

**II: G is time-dependent and matter is covariantly conserved.**

- Solà, J., Gómez-Valent, A., & De Cruz Pérez, J., 2015, ApJ, 811, L14

$$\dot{\rho}_\Lambda + \frac{\dot{G}}{G}(\rho_m + \rho_\Lambda) = 0 \qquad \dot{\rho}_m + 3H\rho_m = 0$$

# Possible consequences of the variation of Λ

**I: G is constant and matter exchanges energy with the vacuum.**

- Gómez-Valent A., Solà J. & Basilakos S., 2015, J. Cosmol. Astropart. Phys. 0402, 006
- Gómez-Valent A. & Solà J.,2015, Mont. Not. Roy. Astron. Soc. 448, 2810-2821

**II: G is time-dependent and matter is covariantly conserved.**

- Solà, J., Gómez-Valent, A., & De Cruz Pérez, J., 2015, ApJ, 811, L14

**III: I+II**

# Possible consequences of the variation of Λ

**I: G is constant and matter exchanges energy with the vacuum.**

- Gómez-Valent A., Solà J. & Basilakos S., 2015, J. Cosmol. Astropart. Phys. 0402, 006
- Gómez-Valent A. & Solà J.,2015, Mont. Not. Roy. Astron. Soc. 448, 2810-2821

**II: G is time-dependent and matter is covariantly conserved.**

- Solà, J., Gómez-Valent, A., & De Cruz Pérez, J., 2015, ApJ, 811, L14

**III: I+II**

# $\Lambda_t G_t$CDM model. Background solutions

$$G1: \qquad \Lambda(H) = 3(c_0 + \nu H^2)$$

$$G2: \qquad \Lambda(H, \dot{H}) = 3(c_0 + \nu H^2 + \frac{2}{3}\alpha \dot{H})$$

# $\Lambda_t G_t$CDM model. Background solutions

$$G1: \quad \Lambda(H) = 3(c_0 + \nu H^2)$$

$$G2: \quad \Lambda(H, \dot{H}) = 3(c_0 + \nu H^2 + \frac{2}{3}\alpha \dot{H})$$

Pressure and Friedmann equations

$$\begin{cases} 3H^2 + 2\dot{H} = -8\pi G(H)\,(p_\Lambda + p_r) \\ 3H^2 = 8\pi G(H)\,(\rho_m + \rho_r + \rho_\Lambda(H)) \end{cases}$$

# $\Lambda_t G_t$CDM model. Background solutions

$$G1: \quad \Lambda(H) = 3(c_0 + \nu H^2)$$

$$G2: \quad \Lambda(H, \dot{H}) = 3(c_0 + \nu H^2 + \frac{2}{3}\alpha \dot{H})$$

Pressure and Friedmann equations

$$\begin{cases} 3H^2 + 2\dot{H} = -8\pi G(H)\,(p_\Lambda + p_r) \\ 3H^2 = 8\pi G(H)\,(\rho_m + \rho_r + \rho_\Lambda(H)) \end{cases}$$

$$\xi = \frac{1-\nu}{1-\alpha} \equiv 1 - \nu_{\rm eff}\,, \quad \xi' = \frac{1-\nu}{1-\frac{4}{3}\alpha} \equiv 1 - \nu'_{\rm eff}$$

# $\Lambda_t G_t$CDM model. Background solutions

$$G1: \quad \Lambda(H) = 3(c_0 + \nu H^2)$$

$$G2: \quad \Lambda(H, \dot{H}) = 3(c_0 + \nu H^2 + \frac{2}{3}\alpha \dot{H})$$

Pressure and Friedmann equations

$$3H^2 + 2\dot{H} = -8\pi G(H)\,(p_\Lambda + p_r)$$

$$3H^2 = 8\pi G(H)\,(\rho_m + \rho_r + \rho_\Lambda(H))$$

$$\xi = \frac{1-\nu}{1-\alpha} \equiv 1 - \nu_{\rm eff}\,, \quad \xi' = \frac{1-\nu}{1-\frac{4}{3}\alpha} \equiv 1 - \nu'_{\rm eff}$$

$$E^2(a) = 1 + \frac{\Omega_m}{\xi}\left[-1 + a^{-4\xi'}\left(a + \frac{\xi\,\Omega_r}{\xi'\Omega_m}\right)^{\frac{\xi'}{1-\alpha}}\right]$$

$G(a) = G_0\, a^{3(1-\xi)}$ MD and ΛD epochs

$G(a) = G_0\, a^{4(1-\xi')}$ RD epoch

# $\Lambda_t G_t$CDM model. Background solutions

Energy densities

Presureless matter $$\rho_m(a) = \rho_m^{(0)} a^{-3}$$

Radiation $$\rho_r(a) = \rho_r^{(0)} a^{-4}$$

Vacuum $$\rho_\Lambda(a) = \rho_{c0}\, a^{-3} \left[ a^{3\xi} + \frac{\Omega_m}{\xi}(1 - \xi - a^{3\xi}) \right]$$

# $\Lambda_t G_t$CDM model. Background solutions

Energy densities

Presureless matter $$\rho_m(a) = \rho_m^{(0)} a^{-3}$$

Radiation $$\rho_r(a) = \rho_r^{(0)} a^{-4}$$

Vacuum $$\rho_\Lambda(a) = \rho_{c0}\, a^{-3} \left[ a^{3\xi} + \frac{\Omega_m}{\xi}(1 - \xi - a^{3\xi}) \right]$$

*All the background functions reduce to the ΛCDM ones in the limit v=α=0 .*

# $\Lambda_t G_t$CDM model. Linear structure formation

The differential equation that governs the behavior of the matter perturbations at the linear level is a third order one:

$$\delta_m''' + \frac{\delta_m''}{2a}(16 - 9\Omega_m) + \frac{3\delta_m'}{2a^2}(8 - 11\Omega_m + 3\Omega_m^2 - a\Omega_m') = 0$$

Initial conditions (z≈100):

$$s = 3\xi - 2$$
$$\delta_m(a_i) = a_i^s$$
$$\delta_m'(a_i) = s a_i^{s-1}$$
$$\delta_m''(a_i) = s(s-1) a_i^{s-2}$$

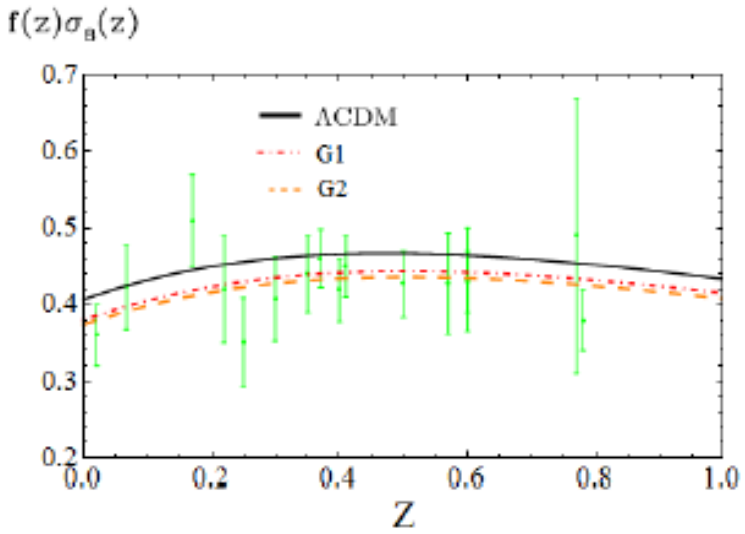
# $\Lambda_t G_t$CDM model. Linear structure formation

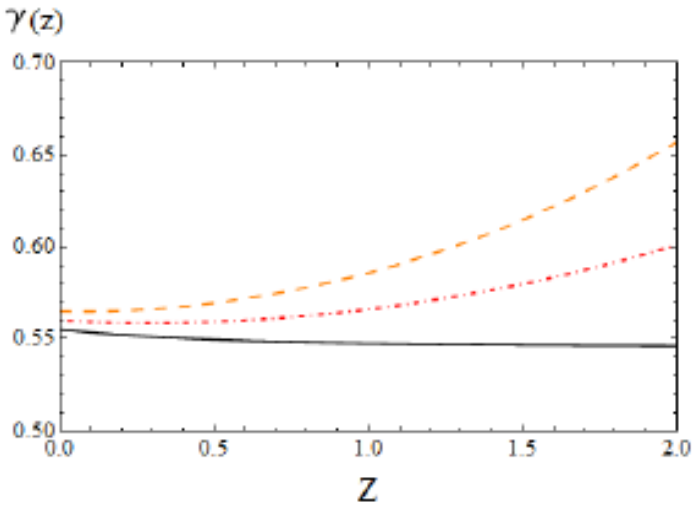
The differential equation that governs the behavior of the matter perturbations at the linear level is a third order one:

$$\delta_m''' + \frac{\delta_m''}{2a}(16 - 9\Omega_m) + \frac{3\delta_m'}{2a^2}(8 - 11\Omega_m + 3\Omega_m^2 - a\Omega_m') = 0$$

The dynamical vacuum models are able to fit fit better the linear structure formation data.

$f(z) = -(1+z)d\ln\delta_m/dz$



# Fitting analysis

Cosmological observables used in this analysis:

1. Union 2.1 set of 580 type Ia supernovae of Suzuki et al 2012.

$$\mu = m - M = 5 \log d_L + 25 \qquad d_L(z, \mathrm{p}) = c(1+z) \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

2. BAO: 6 A(z) points collected in Blake et al 2011.

$$A(z_i, \mathrm{p}) = \frac{\sqrt{\Omega_m^0}}{E^{1/3}(z_i)} \left[ \frac{1}{z_i} \int_0^{z_i} \frac{dz}{E(z)} \right]^{2/3}$$

# Fitting analysis

3. CMB shift parameter of Planck 2015

$$R = \sqrt{\Omega_m^0} \int_0^{z_*} \frac{dz}{E(z)}$$

4. 29 Hubble points through the diagnostic function of Sahni et al. 2014

$$Omh^2_G(z_i, z_j) = \frac{\Omega_m\, h^2}{\xi} \frac{(1+z_i)^{3\xi} - (1+z_j)^{3\xi}}{(1+z_i)^3 - (1+z_j)^3} \qquad \sigma^2_{Omh^2\, i,j} = \frac{4\left[h^2(z_i)\sigma^2_{h(z_i)} + h^2(z_j)\sigma^2_{h(z_j)}\right]}{\left[(1+z_i)^3 - (1+z_j)^3\right]^2}$$

$$\chi^2_{Omh^2} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\frac{Omh^2_{th}(H_i, H_j) - Omh^2_{obs}(H_i, H_j)}{\sigma_{Omh^2\, i,j}}\right]^2$$

5. Average BBN restriction (Chiba et al. 2011, Uzan et al. 2011) $|\Delta G/G| < 10\%$

6. We have required $|\Delta G/G| < 5\%$ at recombination (z ≃ 1100) from the CMB anisotropy spectrum (Chiba et al. 2011)

# Main results. Best-fit values

G1 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (BBN,CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu$ | $\bar{\nu}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1010 | 828.69/1010 | 830.84 | 830.69 |
| G1 | (10%,5%), Yes | $0.278 \pm 0.006$ | $0.275 \pm 0.004$ | $0.0015^{+0.0017}_{-0.0015}$ | $0.0021^{+0.0014}_{-0.0016}$ | 0.797 | 0.784 | 822.82/1009 | 821.97/1009 | 826.82 | 825.97 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/604 | 582.74/604 | 585.38 | 584.74 |
| G1 | (10%,5%), No | $0.290 \pm 0.011$ | $0.281 \pm 0.005$ | $0.0008^{+0.0016}_{-0.0015}$ | $0.0015 \pm 0.0014$ | 0.795 | 0.771 | 577.62/603 | 575.70/603 | 581.62 | 579.70 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/982 | 806.17/982 | 808.68 | 808.17 |
| G1* | (10%,5%), Yes* | $0.296 \pm 0.009$ | $0.287 \pm 0.004$ | $0.0006 \pm 0.0015$ | $0.0012^{+0.0014}_{-0.0013}$ | 0.803 | 0.770 | 802.66/981 | 799.15/981 | 806.66 | 803.15 |

G2 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu_{\text{eff}}$ | $\bar{\nu}_{\text{eff}}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1009 | 828.69/1009 | 830.84 | 830.69 |
| G2 | 5%, Yes | $0.278 \pm 0.006$ | $0.277 \pm 0.004$ | $0.0038^{+0.0025}_{-0.0023}$ | $0.0043^{+0.0018}_{-0.0020}$ | 0.774 | 0.773 | 817.17/1008 | 817.26/1008 | 821.17 | 821.26 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/603 | 582.74/603 | 585.38 | 584.74 |
| G2 | 5%, No | $0.287 \pm 0.011$ | $0.283 \pm 0.005$ | $0.0025^{+0.0026}_{-0.0025}$ | $0.0030^{+0.0021}_{-0.0018}$ | 0.763 | 0.767 | 572.68/602 | 572.99/602 | 576.68 | 576.99 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/981 | 806.17/981 | 808.68 | 808.17 |
| G2* | 5%, Yes* | $0.295 \pm 0.009$ | $0.289 \pm 0.005$ | $0.0015^{+0.0026}_{-0.0025}$ | $0.0028^{+0.0018}_{-0.0021}$ | 0.789 | 0.765 | 798.85/980 | 797.05/980 | 802.85 | 801.05 |

# Main results. Best-fit values

G1 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (BBN,CMB), Omh$^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu$ | $\bar{\nu}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1010 | 828.69/1010 | 830.84 | 830.69 |
| G1 | (10%,5%), Yes | $0.278 \pm 0.006$ | $0.275 \pm 0.004$ | $0.0015^{+0.0017}_{-0.0015}$ | $0.0021^{+0.0014}_{-0.0016}$ | 0.797 | 0.784 | 822.82/1009 | 821.97/1009 | 826.82 | 825.97 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/604 | 582.74/604 | 585.38 | 584.74 |
| G1 | (10%,5%), No | $0.290 \pm 0.011$ | $0.281 \pm 0.005$ | $0.0008^{+0.0016}_{-0.0015}$ | $0.0015 \pm 0.0014$ | 0.795 | 0.771 | 577.62/603 | 575.70/603 | 581.62 | 579.70 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/982 | 806.17/982 | 808.68 | 808.17 |
| G1* | (10%,5%), Yes* | $0.296 \pm 0.009$ | $0.287 \pm 0.004$ | $0.0006 \pm 0.0015$ | $0.0012^{+0.0014}_{-0.0013}$ | 0.803 | 0.770 | 802.66/981 | 799.15/981 | 806.66 | 803.15 |

G2 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (CMB), Omh$^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu_{\text{eff}}$ | $\bar{\nu}_{\text{eff}}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1009 | 828.69/1009 | 830.84 | 830.69 |
| G2 | 5%, Yes | $0.278 \pm 0.006$ | $0.277 \pm 0.004$ | $0.0038^{+0.0025}_{-0.0023}$ | $0.0043^{+0.0018}_{-0.0020}$ | 0.774 | 0.773 | 817.17/1008 | 817.26/1008 | 821.17 | 821.26 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/603 | 582.74/603 | 585.38 | 584.74 |
| G2 | 5%, No | $0.287 \pm 0.011$ | $0.283 \pm 0.005$ | $0.0025^{+0.0026}_{-0.0025}$ | $0.0030^{+0.0021}_{-0.0018}$ | 0.763 | 0.767 | 572.68/602 | 572.99/602 | 576.68 | 576.99 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/981 | 806.17/981 | 808.68 | 808.17 |
| G2* | 5%, Yes* | $0.295 \pm 0.009$ | $0.289 \pm 0.005$ | $0.0015^{+0.0026}_{-0.0025}$ | $0.0028^{+0.0018}_{-0.0021}$ | 0.789 | 0.765 | 798.85/980 | 797.05/980 | 802.85 | 801.05 |

# Main results. Best-fit values

G1 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (BBN,CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu$ | $\bar{\nu}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1010 | 828.69/1010 | 830.84 | 830.69 |
| G1 | (10%,5%), Yes | $0.278 \pm 0.006$ | $0.275 \pm 0.004$ | $0.0015^{+0.0017}_{-0.0015}$ | $0.0021^{+0.0014}_{-0.0016}$ | 0.797 | 0.784 | 822.82/1009 | 821.97/1009 | 826.82 | 825.97 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/604 | 582.74/604 | 585.38 | 584.74 |
| G1 | (10%,5%), No | $0.290 \pm 0.011$ | $0.281 \pm 0.005$ | $0.0008^{+0.0016}_{-0.0015}$ | $0.0015 \pm 0.0014$ | 0.795 | 0.771 | 577.62/603 | 575.70/603 | 581.62 | 579.70 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/982 | 806.17/982 | 808.68 | 808.17 |
| G1* | (10%,5%), Yes* | $0.296 \pm 0.009$ | $0.287 \pm 0.004$ | $0.0006 \pm 0.0015$ | $0.0012^{+0.0014}_{-0.0013}$ | 0.803 | 0.770 | 802.66/981 | 799.15/981 | 806.66 | 803.15 |

G2 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu_{\text{eff}}$ | $\bar{\nu}_{\text{eff}}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1009 | 828.69/1009 | 830.84 | 830.69 |
| G2 | 5%, Yes | $0.278 \pm 0.006$ | $0.277 \pm 0.004$ | $0.0038^{+0.0025}_{-0.0023}$ | $0.0043^{+0.0018}_{-0.0020}$ | 0.774 | 0.773 | 817.17/1008 | 817.26/1008 | 821.17 | 821.26 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/603 | 582.74/603 | 585.38 | 584.74 |
| G2 | 5%, No | $0.287 \pm 0.011$ | $0.283 \pm 0.005$ | $0.0025^{+0.0026}_{-0.0025}$ | $0.0030^{+0.0021}_{-0.0018}$ | 0.763 | 0.767 | 572.68/602 | 572.99/602 | 576.68 | 576.99 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/981 | 806.17/981 | 808.68 | 808.17 |
| G2* | 5%, Yes* | $0.295 \pm 0.009$ | $0.289 \pm 0.005$ | $0.0015^{+0.0026}_{-0.0025}$ | $0.0028^{+0.0018}_{-0.0021}$ | 0.789 | 0.765 | 798.85/980 | 797.05/980 | 802.85 | 801.05 |

# The Akaike information criterion

- Model selection criterion
- It penalizes the use of extra parameters in the model
- Given two competing models describing the same data, the model that does better is the one with smaller AIC value.
- For $N$ observational points and $n_p$ fit parameters it reads:

$$\mathrm{AIC} = -2\ln \mathcal{L}_{\max} + 2n_p + \frac{2n_p(n_p+1)}{N-n_p-1}$$

In case $N/n_p > 40$

If data is normally distributed

$$\mathrm{AIC} = -2\ln \mathcal{L}_{\max} + 2n_p = \chi^2_{\min} + 2n_p$$

# The Akaike information criterion

$$(\Delta\mathrm{AIC})_{ij} = (\mathrm{AIC})_i - (\mathrm{AIC})_j \qquad \Delta_{ij} \equiv |\Delta(\mathrm{AIC})_{ij}|$$

Rule of thumb:

- $\Delta_{ij} < 2$ no evidence
- $6 \geq \Delta_{ij} \geq 2$ weak evidence
- $6 \leq \Delta_{ij}$ strong evidence

# Main results. Best-fit values

Evidence in favour of the dynamical vacuum models!

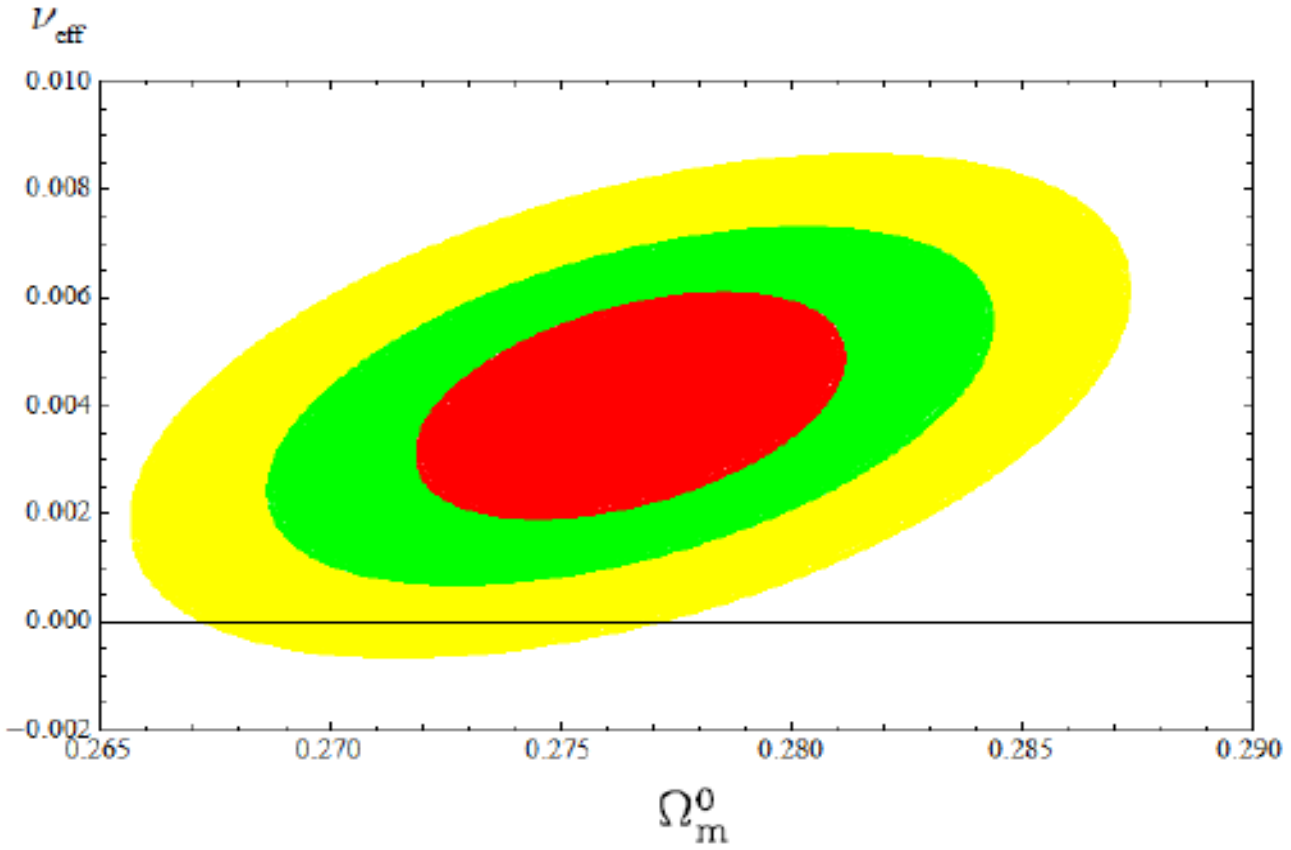
G1 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (BBN,CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu$ | $\bar{\nu}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1010 | 828.69/1010 | 830.84 | 830.69 |
| G1 | (10%,5%), Yes | $0.278 \pm 0.006$ | $0.275 \pm 0.004$ | $0.0015^{+0.0017}_{-0.0015}$ | $0.0021^{+0.0014}_{-0.0016}$ | 0.797 | 0.784 | 822.82/1009 | 821.97/1009 | 826.82 | 825.97 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/604 | 582.74/604 | 585.38 | 584.74 |
| G1 | (10%,5%), No | $0.290 \pm 0.011$ | $0.281 \pm 0.005$ | $0.0008^{+0.0016}_{-0.0015}$ | $0.0015 \pm 0.0014$ | 0.795 | 0.771 | 577.62/603 | 575.70/603 | 581.62 | 579.70 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/982 | 806.17/982 | 808.68 | 808.17 |
| G1* | (10%,5%), Yes* | $0.296 \pm 0.009$ | $0.287 \pm 0.004$ | $0.0006 \pm 0.0015$ | $0.0012^{+0.0014}_{-0.0013}$ | 0.803 | 0.770 | 802.66/981 | 799.15/981 | 806.66 | 803.15 |

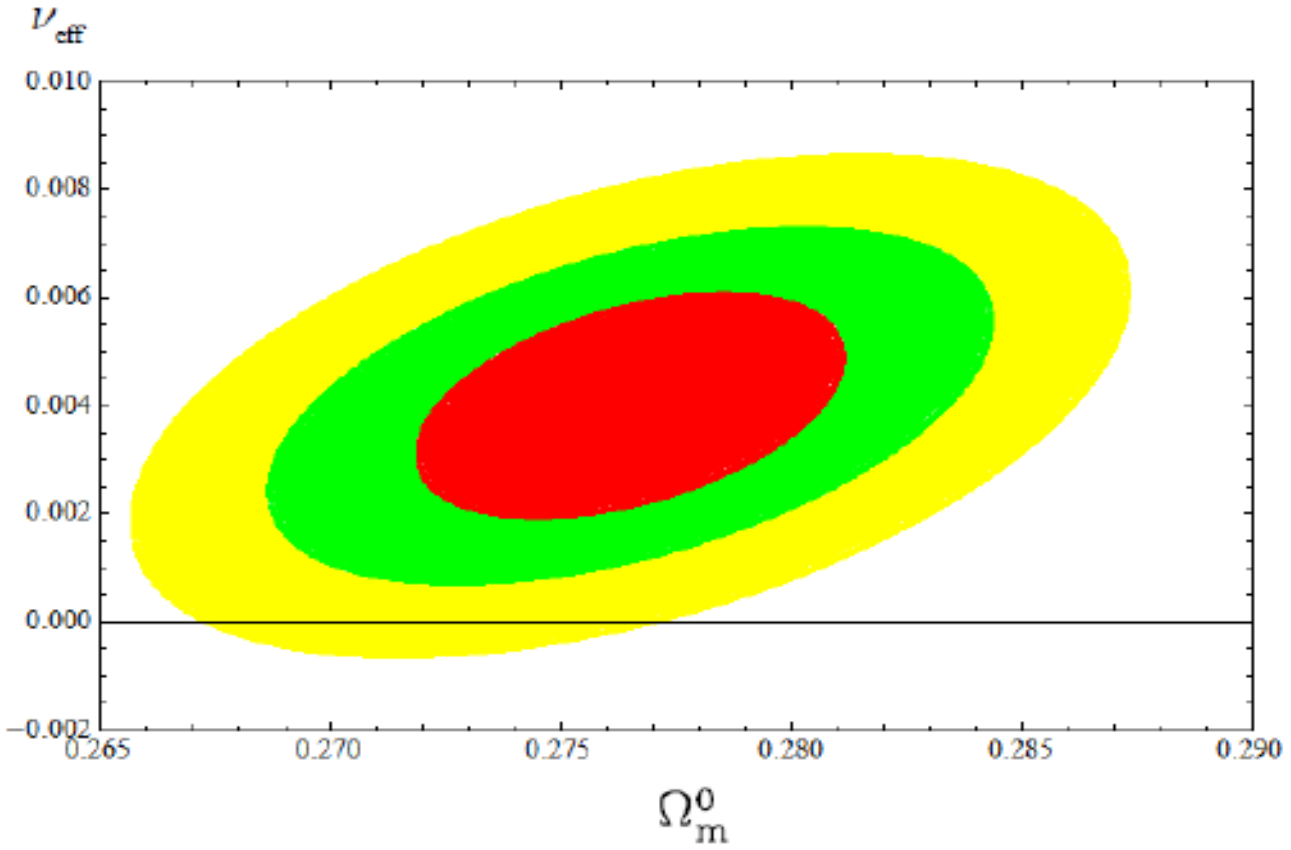
G2 MODEL

| Model | $\lvert\frac{\Delta G}{G_0}\rvert$ (CMB), $Omh^2$ | $\Omega_m$ | $\overline{\Omega}_m$ (all data) | $\nu_{\text{eff}}$ | $\bar{\nu}_{\text{eff}}$ | $\sigma_8$ | $\overline{\sigma}_8$ | $\chi^2/dof$ | $\overline{\chi}^2/dof$ | AIC | $\overline{\text{AIC}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | -, Yes | $0.278^{+0.005}_{-0.004}$ | $0.276 \pm 0.004$ | - | - | 0.815 | 0.815 | 828.84/1009 | 828.69/1009 | 830.84 | 830.69 |
| G2 | 5%, Yes | $0.278 \pm 0.006$ | $0.277 \pm 0.004$ | $0.0038^{+0.0025}_{-0.0023}$ | $0.0043^{+0.0018}_{-0.0020}$ | 0.774 | 0.773 | 817.17/1008 | 817.26/1008 | 821.17 | 821.26 |
| $\Lambda$CDM | -, No | $0.292 \pm 0.008$ | $0.286 \pm 0.007$ | - | - | 0.815 | 0.815 | 583.38/603 | 582.74/603 | 585.38 | 584.74 |
| G2 | 5%, No | $0.287 \pm 0.011$ | $0.283 \pm 0.005$ | $0.0025^{+0.0026}_{-0.0025}$ | $0.0030^{+0.0021}_{-0.0018}$ | 0.763 | 0.767 | 572.68/602 | 572.99/602 | 576.68 | 576.99 |
| $\Lambda$CDM* | -, Yes* | $0.297 \pm 0.006$ | $0.293 \pm 0.006$ | - | - | 0.815 | 0.815 | 806.68/981 | 806.17/981 | 808.68 | 808.17 |
| G2* | 5%, Yes* | $0.295 \pm 0.009$ | $0.289 \pm 0.005$ | $0.0015^{+0.0026}_{-0.0025}$ | $0.0028^{+0.0018}_{-0.0021}$ | 0.789 | 0.765 | 798.85/980 | 797.05/980 | 802.85 | 801.05 |

# Main results. Contour lines

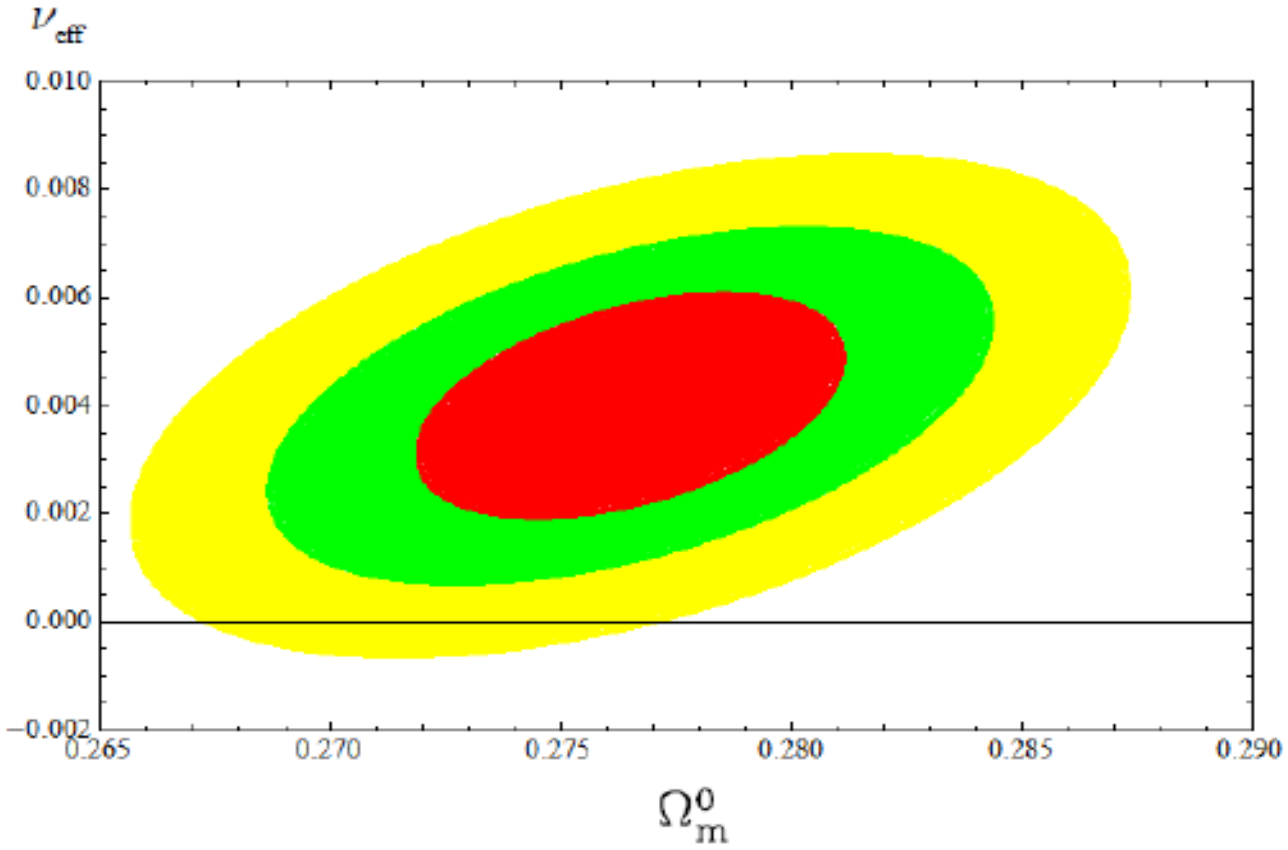


# Main results. Contour lines




ΛCDM is disfavored at ≈3σ level

# Main results. Contour lines




ΛCDM is disfavored at ≈3σ level

$$\mathrm{ER} = e^{\overline{\Delta}_{ij}/2}$$

$$\gtrsim 111.6 \text{ for G2}$$

$$\gtrsim 10.6 \text{ for G1}$$

# Summary

1. We have analyzed some dynamical vacuum models, in which the vacuum energy densities dependence on the Hubble functions is motivated from RG arguments in QFT in curved space-time.

# Summary

1. We have analyzed some dynamical vacuum models, in which the vacuum energy densities dependence on the Hubble functions is motivated from RG arguments in QFT in curved space-time.

2. These kind of models are able to fit considerably better the current observational data than the concordance LCDM one at a confidence level of 3σ.

# Thank you very much for your attention

adriagova@ecm.ub.edu