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Constraining modified gravity with galaxy bispectrum

DY, S.Yokoyama, H.Tashiro, PRD96, 123516(2017)

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Modified gravity theories

- General relativity : massless spin-2
- Modified gravity : A new d.o.f. is introduced to achieve the accelerating expansion

  f(*R*), DGP, Galileons, (beyond-)Horndeski, massive gravity, …

  ✓ Scalar-tensor theories

  - Gravity is mediated by $g_{\mu\nu}$ and ϕ
  - Can capture essential modification of gravity

Why modified gravity?

- Discovery of cosmic acceleration

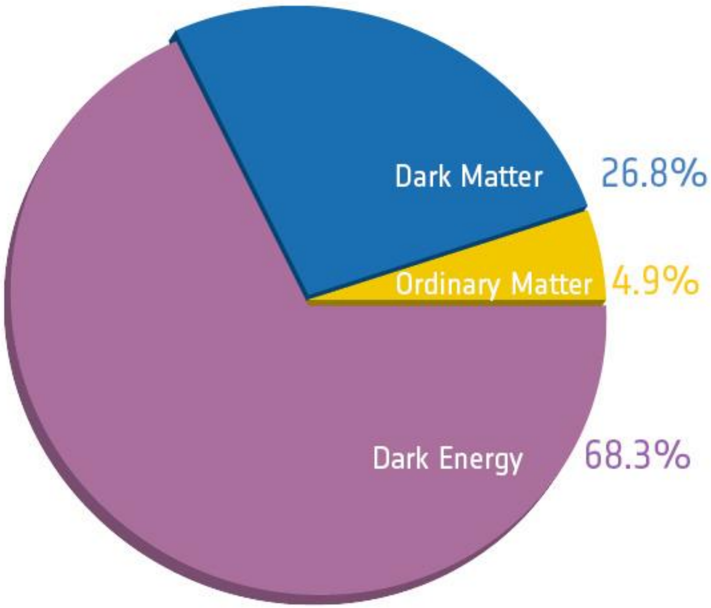
  : Our understanding of the Universe is incomplete!

- Need better understanding of gravity:

  -- Dark energy or modified gravity ?

  - Small scale : consistent with experiments in the solar-system and on the Earth
  - Large scale : can be tested though the cosmological observations

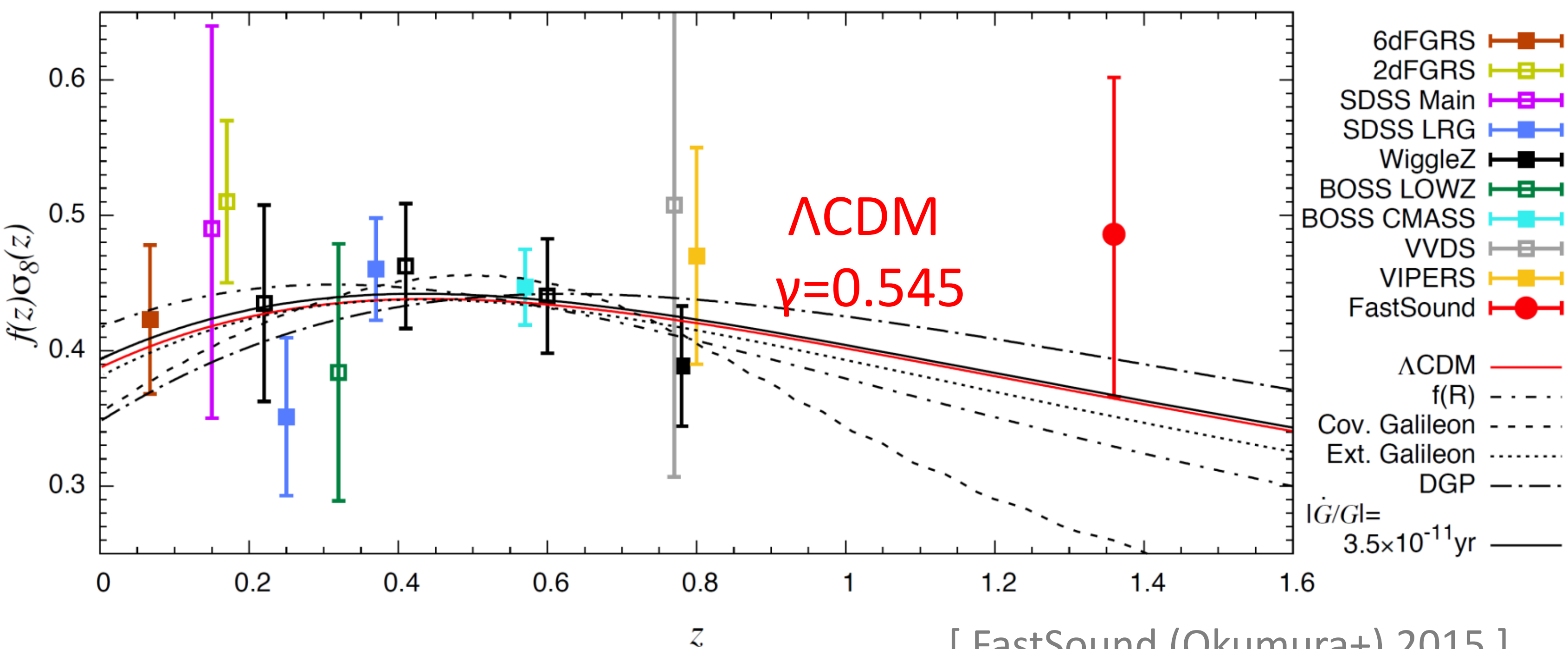
[Planck2013]



Constraining modified gravity with LSS

➢ Gravitational growth index γ : $f(a) = \Omega_m(a)^\gamma$

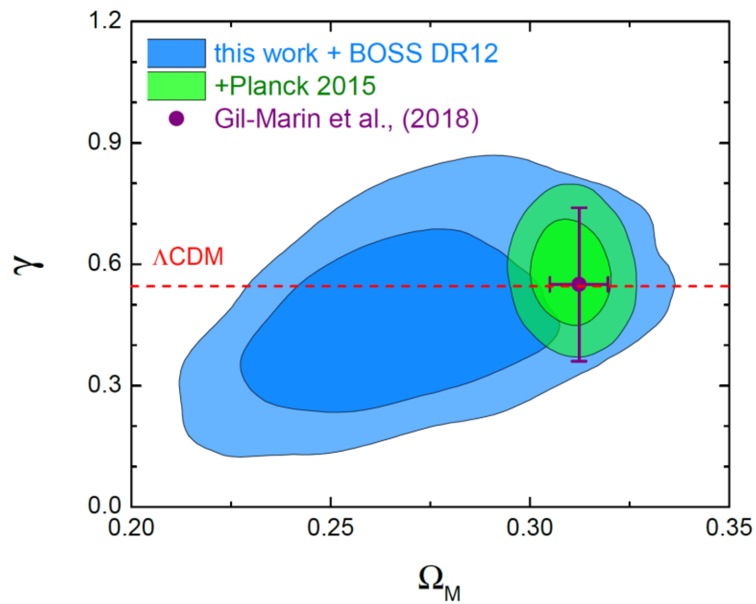
- a powerful tool to test the modified gravity responsible for the present cosmic acceleration

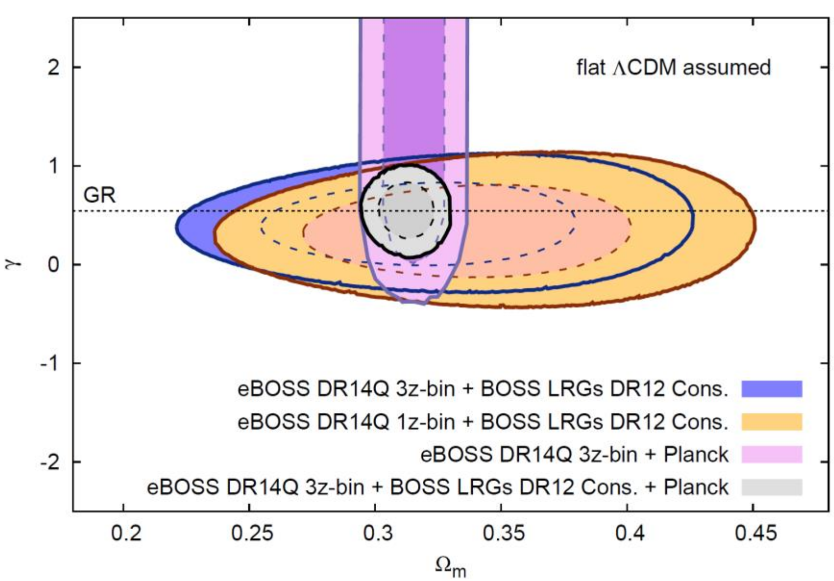


[FastSound (Okumura+) 2015]

Current constraint on growth index γ

γ = 0.566 +- 0.056 (68%CL) [Mueller+(2016) : SDSS-III]
γ = 0.609 +- 0.079 (95%CL) [Sanchez+(2017) : SDSS-III]
γ = 0.54 +- 0.11 (68%CL) [Grieb+(2016) : SDSS-III]
γ = 0.580 +- 0.082 (95%CL) [Zhao+(2018) : eBOSS DR14]
γ = 0.54 +- 0.19 (95%CL) [Gil-Marin(2018) : eBOSS DR14]





Is γ enough?

- Need new possible parameterizations to capture the essence of the modified gravity theory!

  --*Quasi*-nonlinearity of the growth
  as a way to provide new insight

  - Late-time nonlinear gravitational evolution have new information, which would not be imprinted on the growth index

⇨ **Second-order index**

Second-order index ξ

- Gravitational growth index γ : $f(a) = \Omega_m(a)^{\gamma}$

-- In order to compare the observational data and theoretical predictions efficiently, introducing γ should be useful.

However,

-- There are many models in which the expansion history and the growth rate are same in the fiducial model.

-- The new parameter is needed to distinguish and hopefully exclude these model !

- Second-order index ξ : $\lambda(a) = \Omega_m(a)^{\xi}$

Evolution of density perturbation

- The governing equations for matter fluctuations:

$$
\begin{cases}
\delta_m + (1/a)\nabla \cdot [(1+\delta_m)\mathbf{v}] = 0 \\
\mathbf{v} + H\,\mathbf{v} + (1/a)(\mathbf{v} \cdot \nabla)\,\mathbf{v} = -(1/a)\nabla \Phi
\end{cases}
$$

The effect of the gravity theory on the evolution of the matter perturbations δ_m appears only through the gravitational potential Φ.

Bispectrum due to nonlinear growth

$$B(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3;z) = 2D^4(z)\, Z_1(\boldsymbol{k}_1;z) Z_1(\boldsymbol{k}_2;z) Z_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) P(k_1) P(k_2) + \mathrm{cyc}$$

with $Z_1(\boldsymbol{k};z) = b_1 + f\mu^2$

$$Z_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) = b_2/2 + b_1\, F_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) + f\mu_{12}{}^2\, G_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) + \ldots$$

F_2, G_2 have information of nonlinear growth

- Second-order perturbative kernel

$$F_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) = \alpha_s(\boldsymbol{k}_1,\boldsymbol{k}_2) - (2/7)\, \lambda(z)\, \gamma_s(\boldsymbol{k}_1,\boldsymbol{k}_2)$$

$$G_2(\boldsymbol{k}_1,\boldsymbol{k}_2;z) = \alpha_s(\boldsymbol{k}_1,\boldsymbol{k}_2) - (4/7)\, \lambda_\theta(z)\, \gamma_s(\boldsymbol{k}_1,\boldsymbol{k}_2)$$

[$\lambda=\lambda_\theta=1$ in EdS , $\lambda,\lambda_\theta \fallingdotseq 1$ in ΛCDM [Scoccimarro+Couchiman (2001)]]

[Horndeski (1974),Deffayet+ (2011),Kobayashi+ (2011)]

Horndeski theory

: The most general scalar-tensor theory with second-order field equations.

$$
\begin{aligned}
\mathcal{L} =& G_2(\phi, X) - G_3(\phi, X)\Box\phi \\
&+ G_4(\phi, X)R + \frac{\partial G_4}{\partial X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] \\
&+ G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi \\
&- \frac{1}{6}\frac{\partial G_5}{\partial X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi\,(\nabla_\mu\nabla_\nu\phi)^2 + 2\,(\nabla_\mu\nabla_\nu\phi)^3\right]
\end{aligned}
$$

- ✓have 4 arbitrary functions of ϕ and $X=-1/2(\nabla\phi)^2$.
- ✓is quite useful for a comprehensive study of modified gravity.

EFT Parametrization

Instead of considering the Horndeski functions $G_a(\phi,X)$, the EFT parameters is used to specified the cosmological information :

- Linear perturbation

  M : effective Planck mass

  α_M : Planck mass run rate $\alpha_M = d\log M^2/d\log a$

  α_T : GW (tensor) speed excess $c_T{}^2 = 1 - \alpha_T$

  α_B : braiding

  α_K : kineticity

  [Bellini+Sawicki (2014), Gleyzes+(2013), Bloomfield (2013), (see also Creminelli+(2009), Gubitosi+(2013), Bloomfield(2012))]

- To include the 2nd order perturbations, two other functions are required

  α_{V1} , α_{V2} : Vainshtein screening amplitude [(see also Bellini+(2015))]

[Takushina+Terukina+Yamamoto (2014), Kimura+Kobayashi+Yamamoto(2012)]

Small-scale effective Lagrangian

- Impose quasi-static approximation
- Neglect the higher order metric perturbations Ψ & Φ
- Keep all terms with second-derivative of $Q = H\,\delta\varphi$

: $\nabla^2 Q$ can be large, leading to self-screening in the vicinity of source

- Linear order

$$L_{\rm eff}^{(2)} = aM^2 \left[2\Psi\nabla^2\Phi - (1+\alpha_T)\Psi\nabla^2\Psi - (\alpha_T+\ldots)Q\nabla^2 Q - 2\alpha_B\Phi\nabla^2 Q + 2(\alpha_M-\alpha_T)\Psi\nabla^2 Q \right]$$

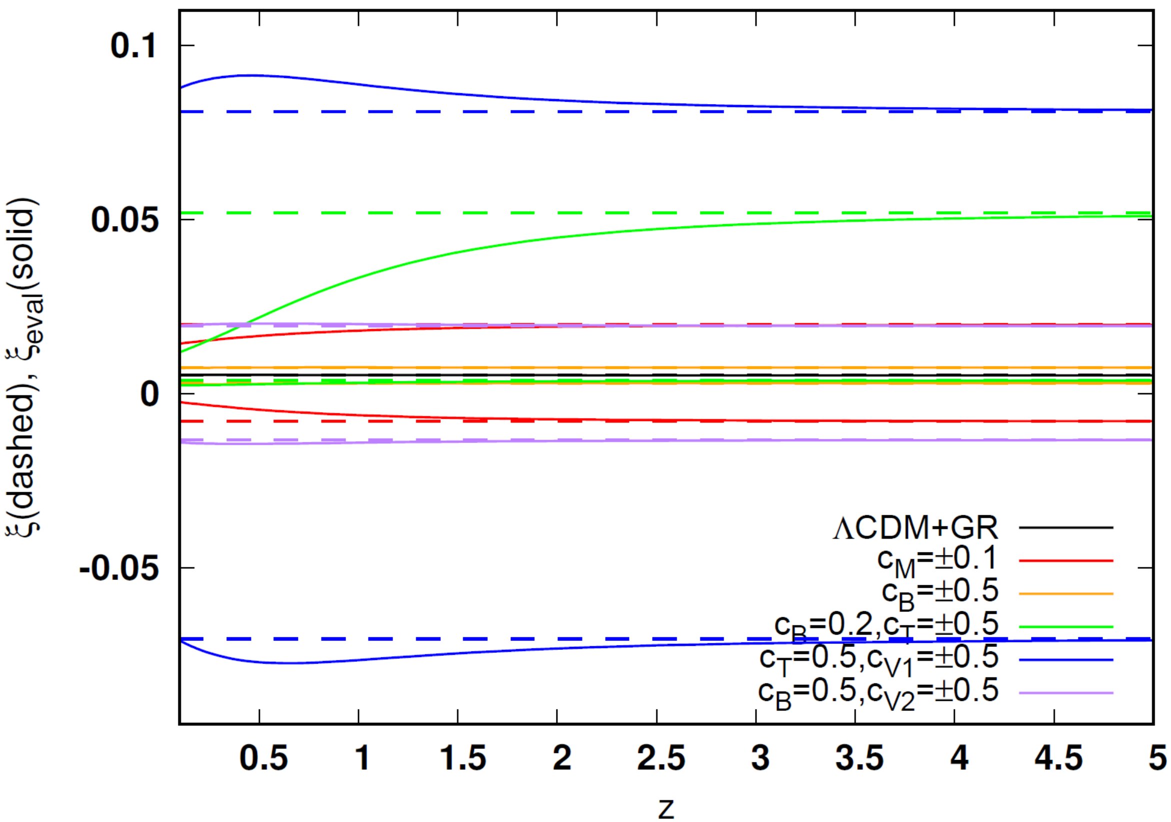
- Nonlinear order

$$L_{\rm eff}^{(NL)} = M^2/aH^2 \left[-(\alpha_{V1}+\ldots)\, L_3^{\rm Gal} + (\alpha_{V1}+\alpha_{V2})\Phi E_3^{\rm Gal} - (1/2)(\alpha_{V2}+\ldots)\Psi E_3^{\rm Gal} + \ldots \right]$$

[see Kobayashi+Watanabe+**DY**(2014),Hirano+Kobayashi+Tashiro+Yokoyama(2018) for GLPV]

Second-order index ξ in Horndeski

- Second-order index ξ : $\lambda(a) = \Omega_m(a)^{\xi}$



Large ξ model can be realized in Horndeski !

$\xi_{\Lambda CDM+GR} = 3/572 \sim 0.00524$

Simple model

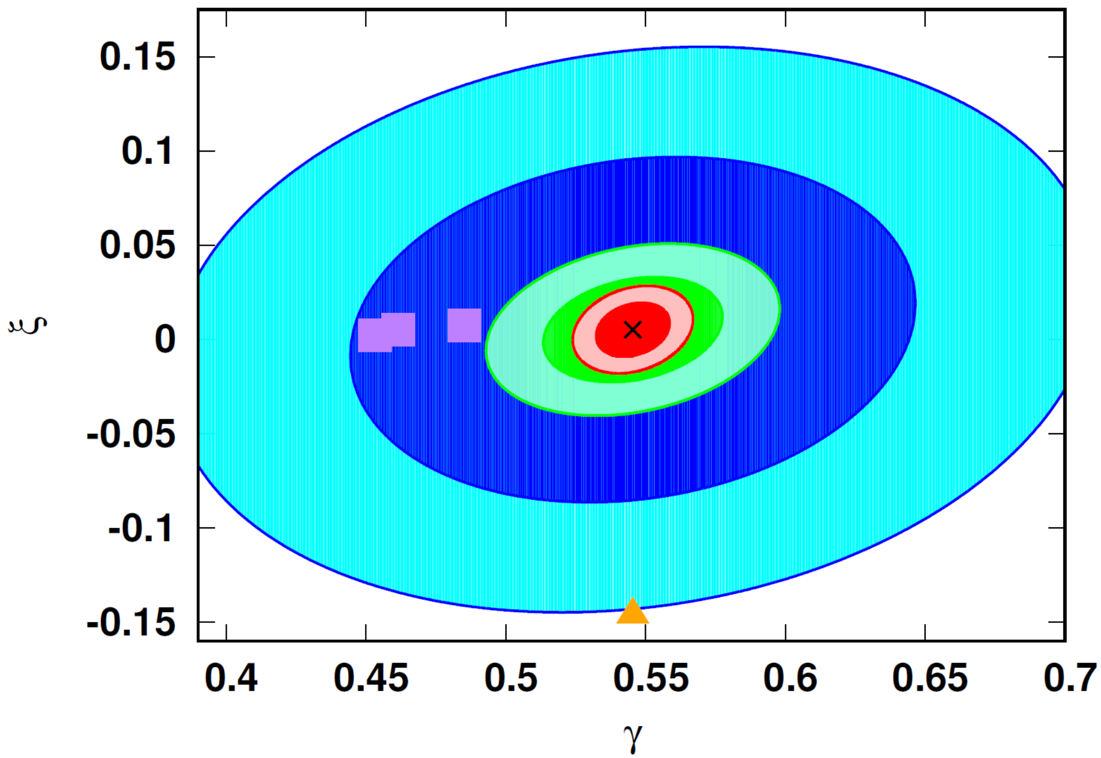
- Assume that ΛCDM as the background expansion, namely w(0)=-1.
- Taking the small braiding limit cB→0, the situation is drastically simplified :

$$\gamma(c_{\rm B}=0) = \frac{3(2-c_{\rm M})}{11+2c_{\rm M}},$$

$$\xi(c_{\rm B}=0) = \frac{3}{8(4+c_{\rm M})(13+2c_{\rm M})}\left[\frac{(8+c_{\rm M})(1-26c_{\rm M})}{11+2c_{\rm M}} + 21\,(c_{\rm M}-1)\,c_{\rm V1}\right].$$

- γ and ξ depend only on c_M and c_{V1}.
- We can realize the large ξ model in the case which can not be distinguished with the standard ΛCDM with GR up to the linear growth of density fluctuations!

Fisher analysis



Survey	Δw_{DE}	$\Delta\gamma$	$\Delta\xi$
SKA1MID	0.135	0.067	0.060
SKA2	0.0085	0.0087	0.0094
Euclid	0.016	0.021	0.018

Summary

- Measuring the galaxy bispectrtum induced by the late-time nonlinear gravitational evolution of the density fluctuations can be used to test the gravity theory through the linear growth rate and the second-order kernel.

  - ✓ Second-order index ξ : $\lambda(a) = \Omega_m(a)^{\xi}$

Large ξ model

- Set the form of Horndeski functions : $G_5 = 0$

$$K = -c_2 M_2^4 \left(\frac{X}{M_2^4}\right)^{p_2}, \quad G_3 = c_3 M_3 \left(\frac{X}{M_3^4}\right)^{p_3}, \quad G_4 = \frac{M_*^2}{2} - c_4 M_4^2 \left(\frac{X}{M_4^4}\right)^{p_4}$$

- Search tracker solution, which is characterized by the condition

$$H\dot{\phi}^{2q} = \text{const.} \quad \Rightarrow \quad p_2 = p\,, \quad p_3 = p + q - \frac{1}{2}\,, \quad p_4 = p + 2q\,.$$

- Solving the background EoMs, the EFT parameters are given by

$$\alpha_{\rm B} = 2p\left(1 - \tilde{\Omega}_{\rm m}\right) - 2\alpha_{\rm V1}\,, \quad \alpha_{\rm K} = 6q\alpha_{\rm B}$$

$$\alpha_{\rm M} = \frac{3}{2q}\tilde{\Omega}_{\rm m}\frac{\alpha_{\rm V1}}{1-\alpha_{\rm BK}}\,, \quad \alpha_{\rm T} = \frac{2\alpha_{\rm V1}}{1-2p-4q}$$

- Consider the small braiding limit and the large hierarchy |p/q|<<1:

$$\gamma \approx 0.545\,, \quad \xi \approx 0.005 - 0.151p$$

Scalar-tensor theory after **GW170817**

New constraint brought by the discovery of a GW event and its optical counterpart

- ✓ The speed of gravitational waves ("c_{GW}") and that of light ("c") coincide to a very high precision :

$$-3 \times 10^{-15} < \alpha_T < 6 \times 10^{-16}$$

- ✓ Several possibilities :
  - ☐ (Extreme) fine-tuning
  - ☐ This observation is a strong indication that "c_{GW}" and "c" strictly coincide : $c_{GW}=c$