Asymptotic Safety and Cosmic Coincidence problem

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Series of papers about gravity phenomenology inspired/compatible with Asymptotic Safety Framework for Quantum Gravity

Fotios Anagnostopoulos

Alfio Bonanno

Spiros Basilakos

Georgios Kofinas

Ayan Mitra

1. **Avoidance of singularities in asymptotically safe Quantum Einstein Gravity**
Georgios Kofinas, Vasilios Zarikas
Published in JCAP 1510 (2015) no.10069

2. **Asymptotic Safe gravity and non-singular inflationary Big Bang with vacuum birth**
Georgios Kofinas, Vasilios Zarikas.
Published in Phys. Rev D 2016
Physical Review D - Particles, Fields, Gravitation and Cosmology, Vol. 94, 10, 2016, 103514

3. **A solution of the dark energy and its coincidence problem based on local antigravity sources without fine-tuning or new scales**
Georgios Kofinas, Vasilios Zarikas. Phy.Rev D 2018.

4. F.K.Anagnostopoulos, S.Basilakos, G.Kofinas, V. Zarikas, ``Constraining the Asymptotically Safe Cosmology: cosmic acceleration without dark energy," JCAP \textbf{02}, 053 (2019)

5. V. Zarikas and G.Kofinas,
`Singularities and Phenomenological aspects of Asymptotic Safe Gravity,‘
J. Phys. Conf. Ser. \textbf{1051}, no.1, 012028 (2018)

6. F.K.Anagnostopoulos, G.Kofinas and V.Zarikas
`IR quantum gravity solves naturally cosmic acceleration and its coincidence problem," Int. J. Mod. Phys. D \textbf{28}, no.14, 14 (2019)

7. Effective field equations and scale-dependent couplings in gravity," Phys. Rev. D {103}, no.10, 104025 (2021)

8. A.Mitra, V. Zarikas, A.Bonanno, M. Good ``Constraining the Swiss-Cheese IR-Fixed Point Cosmology with Cosmic Expansion,"
Universe {7}, no.8, 263 (2021)

9. F. K. Anagnostopoulos, A.Bonanno, A.Mitra and V. Zarikas, ``Swiss-cheese cosmologies with variable G and \Lambda from the renormalization group,"
Phys. Rev. D {105}, no.8, 083532 (2022)

Swiss Cheese cosmology for Asymptotic Safe gravity and phenomenological results

Gravity and UV completion

- Three main attempts of quantum gravity try to address the description of gravity at the fundamental level

- String-branes theory / M theory
- Loop gravity ,   Causal set framework
- Asymptotic safe program (and similar RG approaches)

UV-completion requires new physics:

- **String theory:**
  - unifies all forces of nature
  - requires: supersymmetry, extra dimensions
  - no predictability
  - contains singularities!!!
  - measurement problem

- **Loop - Causal set models for quantum gravity:**
  - Discrete geometry
  - keeps Einstein-Hilbert action as "fundamental"
  - new quantization scheme
  - Absence of mathematical tools
  - measurement problem ??
  - Background independent approach

The most minimal framework

- **Asymptotic safety (AS)** works in 4-dim

  Minimal proposal keeps the same symmetries and fields of Quantum Field Theory(i.e. SM) and General Relativity (GR)
- It was able to indicate that GR can be non-perturbatively renormalizable theory
- not a complete framework
- measurement problem: is it able only partially to describe in a satisfactory way the passage from quantum to classical spacetimes …
- Background independent approach

Steps of AS

Theory

Field contents (e.g. graviton)+
+symmetries (e.g. coordinate trns)

Action

Specific interactions of fields
that respect symmetries (e.g. $\sqrt{g}R$)

Theory space

Space containing all actions
with "coordinates" coupling constants (e.g. G, Λ)

Renormalization group flow:

Connects physics at different scales k,
G, Λ running coupling constants

AS can be understood with QFT concepts and tools

- Quantum Field Theory (QFT) provides a framework where we treat quantum systems with many degrees of freedom and many orders of magnitude in length, or in energy, momentum.

- However, the measurements are typically performed at low energies, in the infrared (IR) regime. We need also a theory where those quantum fluctuations or modes are taken into account for an energy which is between the UV and IR energy scales. The functional renormalization group (RG) method is one of the best candidates to take into account the quantum fluctuations step by step, one by one, systematically

AS and UV completion

- In quantum field theory, observable quantities such as decay rates and cross sections can be expressed as functions of the couplings.
- Generically, if the couplings are finite, also the observable quantities will be finite. So a way of ensuring that our description of the world has a good ultraviolet limit is to require that it lies on a renormalization group trajectory for which all couplings remain finite when the energy goes to infinity.
- The simplest way of achieving this is to demand that the trajectory flows towards a fixed point.

- Based on RG ideas Weinberg realized in 1976 that perturbative renormalizability is not the only way for a theory to remain meaningful at high energies. It is sufficient to fix, at UV energies, only a finite number of parameters. And none of these parameters should become infinite itself in that limit.

- These two requirements: A finite number of finite parameters that determine the theory at high energies are what make a **theory asymptotically safe.**

- This then raises the question of whether quantum gravity, though pertubatively nonrenormalizable, might be asymptotically safe and meaningful after all. This motivation initiated the “asymptotically safe gravity” AS program.

- While the general idea has been around for many years, it has only been in the late 1990s, following works by Wetterich and Reuter, that asymptotically safe gravity has been formulated.

Asymptotic Safety

- The mathematical technique that gave boost to the asymptotic safety scenario is the functional renormalization group equation for gravity [M. Reuter 1998] which enabled the detailed analysis of the gravitational RG flow at the non-perturbative level.

- This technique uses a Wilsonian RG flow on a space of all theories that consists of all difeomorphism invariant functionals of the metric $g_{\mu\nu}$

- The framework emerging from this construction is called Asymptotic Safety or Quantum Einstein Gravity (QEG).

problem

In Einstein's theory, the strength of the gravitational coupling is the number $\check{G}=G\,k^2$, where G is Newton's constant
and k is some momentum scale of the process being considered.
The reason why the energy scale k appears is that gravity couples to mass, and energy is mass;
the higher the energy of a particle the stronger its gravitational coupling.

solution

Newton's constant becomes a running coupling $\boldsymbol{G(k)}$
and it is conceivable that for large $\boldsymbol{k}$ it behaves like $\boldsymbol{k^{-2}}$;
then *the dimensionnelss* $g_k=G(k)\,k^2$ would tend to a constant.

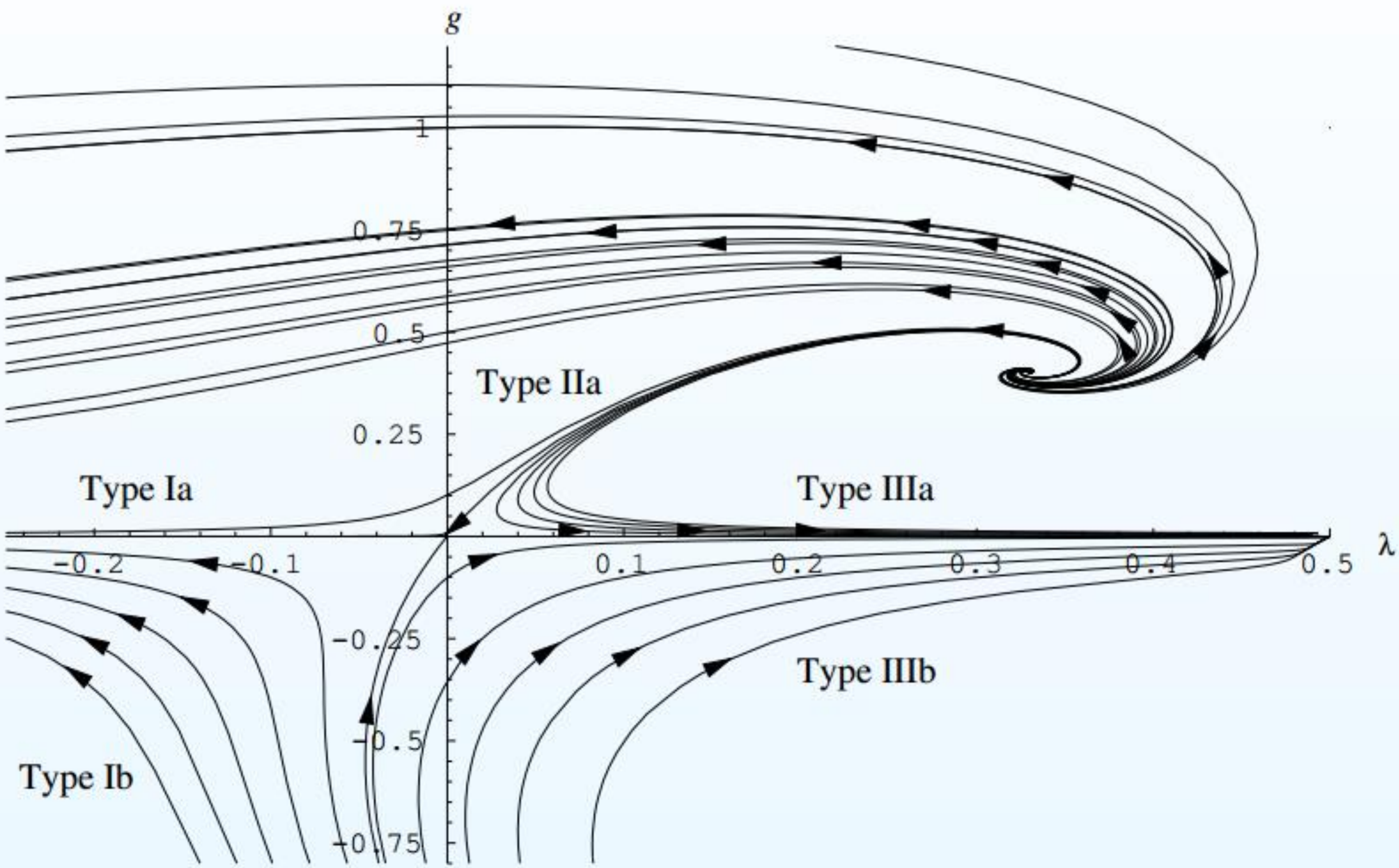
This is what is meant by a fixed point for Newton's constant.

It implies that at some point the dimensionless strength
of the gravitational coupling would
cease growing with the energy and would tend to a finite limit.

$$g_k \equiv k^2 G_k \quad , \quad \lambda_k \equiv k^{-2} \Lambda_k \, ,$$

Einstein-Hilbert-truncation: the phase diagram

M. Reuter and F. Saueressig, Phys. Rev. D **65** (2002) 065016 [hep-th/0110054]



Motivation

We have to explain “naturally”

- A. Recent passage from deceleration to acceleration
- B. Why now? Coincidence problem

As far as I know all papers that explain the first problem have a fine tuning problem exactly like ΛCDM and they don’t explain convincedly the second problem, **with the exception** of papers that connect the recent passage to large scale structure inhomogeneities'. These works solve “naturally” the second problem but->

Motivation

We have to explain "naturally"

A. Recent passage from deceleration to acceleration

B. Why now? Coincidence problem

- However, these works that consider the inhomogeneities to explain both these problems fail to provide enough acceleration (so only partially they solve the first problem).
- Our idea was to accept that the large scale structure plays a significant role and to successfully address both the questions assuming that the acceleration is coming from an effective cosmological constant that its magnitude is associated with the energy density of the astrophysical system under consideration.

Motivation

We have to explain "naturally"

- *Recent passage from deceleration to acceleration*
- *Why now? Coincidence problem*

Effective cosmological constant that it's magnitude is associated with the energy density of the astrophysical system under consideration.?? How this can be true? This is an inherit property of Asymptotic Safety scenario!!!

What about fine tuning

The remarkable thing was that the proposed mechanism lacks also of a fine tuning problem!!! Why? Because astrophysical inhomogeneities length scale is connected with the today value of the cosmological constant needed to explain the amount of cosmic acceleration !!!!

A novel idea is proposed for a natural solution of the dark energy and its cosmic coincidence problem.

The existence of local antigravity sources, associated with astrophysical matter configurations distributed throughout the universe, can lead to a recent cosmic acceleration effect.

A novel idea is proposed for a natural solution of the dark energy and its cosmic coincidence problem.

Various physical theories can be compatible with this idea, but here, in order to test our proposal, we focus on quantum originated spherically symmetric metrics matched with the cosmological evolution through a Swiss cheese analysis.

IR corrections

The proposed solution is based on the simple idea that the acceleration/dark energy can be due to infrared modifications of gravity at intermediate astrophysical scales which effectively generate local antigravity effects.

The cosmological consequence of all these homogeneously distributed local antigravity sources is an overall cosmic acceleration through the matching between the local and the cosmic patches.

Structure formation is crucial

Before the appearance of astrophysical structures (galaxies, clusters of galaxies), such antigravity effects do not exist, and therefore, the recent emergence of acceleration is not a coincidence but an outcome of the recent formation of structure. Before the appearance of structure and the emergence of sufficient repulsive effects, the conventional deceleration scenario is expected.

Asymptotic safe gravity corrections works!

In the context of asymptotically safe gravity, we have explained the observed amount of dark energy using the galaxy or cluster length scales, and dimensionless order one parameters predicted by the theory, without fine-tuning or extra unproven energy scales.

Corrected Schwarzschild-de Sitter metric

The interior modified Schwarzschild-de Sitter metric used in a swiss cheese model, allows us to approximately interpret the observed "cosmological constant ΛCDM" as a composite quantity (generated by adding all local antigravity sources) instead of being a fundamental one.

AS corrected Schwarzschild-de Sitter metric

- Our swiss cheese model matches a homogeneous and isotropic cosmological metric with the AS corrected Schwarzschild-de Sitter metric

$$ds^2 = -\left(1 - \frac{2G_kM}{R} - \frac{1}{3}\Lambda_k R^2\right)dT^2 + \frac{dR^2}{1 - \frac{2G_kM}{R} - \frac{1}{3}\Lambda_k R^2} + R^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

A Swiss cheese model with spherical symmetry overcomes the difficulty of how to glue a static solution of the theory at hand within a larger time-dependent homogeneous and isotropic spacetime.

The idea is to assume a very large number of local objects homogeneously and isotropically distributed in the universe. The matching of a spatially homogeneous metric as the exterior spacetime to a local interior solution has to be realized across a spherical boundary that stays at a fixed coordinate radius in the cosmological frame while evolves in the interior frame.

$r = r_\Sigma$

- In cosmological metric coordinates, a spherical boundary is defined to have a fixed coordinate radius $r = r_\Sigma$, with r_Σ, constant. Of course, this boundary is seen by a cosmological observer to expand, following the universal expansion.

Two matching conditions

Let us consider a four-dimensional manifold M with metric $g_{\mu\nu}$ and a timelike hypersurface Σ which splits the spacetime M into two parts.

Continuity of the spacetime across the hypersurface Σ implies that h_{ij} (induced metric) is continuous on Σ, which means that h_{ij} is the same when computed on either side of Σ.

Two matching conditions

If we consider Einstein gravity with a regular spacetime matter content and vanishing distributional energy-momentum tensor on Σ, then the Israel-Darmois matching conditions imply that the sum of the two extrinsic curvatures computed on the two sides of Σ is zero.

We much a homogeneous and isotropic cosmological metric

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)\right],$$

With metric representing a static spherically symmetric spacetime in Schwarzschild-like coordinates

The interior metric $r<r_\Sigma$ is replaced by the following metric

$$ds^2 = -J(R)F(R)dT^2 + \frac{dR^2}{F(R)} + R^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right) ,$$

First condition

$$JF\left(\frac{dT_S}{dt}\right)^2 - \frac{1}{F}\left(\frac{dR_S}{dt}\right)^2 = 1$$

$$R_S = a r_\Sigma \,.$$

Second condition

$$\frac{d^2T_S}{dt^2} = -\epsilon\sqrt{1-\kappa r_\Sigma^2}\,\frac{(F\sqrt{J})'}{F^2J}\,\frac{dR_S}{dt}$$

$$\frac{d^2R_S}{dt^2} = -\frac{F'}{2}\,.$$

If the black hole is described by the classical Schwarzschild solution we recover the dust FRW

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{2G_N M}{r_\Sigma^3 a^3} - \frac{\kappa}{a^2},$$

$$\frac{\ddot{a}}{a} = -\frac{G_N M}{r_\Sigma^3 a^3},$$

We are interested for Infrared regime of RG flow according to AS

$$G(k)_{IR} = \frac{g_*}{k^2} + h_1 k^{\theta_1 - 2} \qquad \Lambda(k)_{IR} = \lambda_* k^2 + h_2 k^{\theta_2 + 2}$$

Energy/momentum measure should be connected with a length scale

In order to proceed further, the energy measure k has to be connected with a length scale L,

$$k = \xi / L,$$

where ξ is a dimensionless parameter

Scaling

$$k_S = \frac{\xi}{R_S} \, .$$

$$k_S = \frac{\xi}{D_S} \, ,$$

$$D_S = \int_{R_1}^{R_S} \frac{dR}{\sqrt{F(R)}}$$

Scaling as k=ξ/Ds

$$q(z) = \Bigg[6JMD_p(z)^5\left(h_1\left(\frac{\xi}{D_p(z)}\right)^{\theta_1}+g_*\right)+\frac{6\sqrt{3}Mr_\Sigma D_p(z)^4\left(h_1(\theta_1-2)\left(\frac{\xi}{D_p(z)}\right)^{\theta_1}-2g_*\right)}{z+1}$$

$$-\frac{2J\xi^4 r_\Sigma^3 D_p(z)\left(h_2\left(\frac{\xi}{D_p(z)}\right)^{\theta_2}+\lambda_*\right)}{(z+1)^3}+\frac{\sqrt{3}\xi^4 r_\Sigma^4\left(h_2(\theta_2+2)\left(\frac{\xi}{D_p(z)}\right)^{\theta_2}+2\lambda_*\right)}{(z+1)^4}\Bigg]/c$$

$$c = 2y\left(6MD_p(z)^5\left(h_1\left(\frac{\xi}{D_p(z)}\right)^{\theta_1}+g_*\right)+\frac{\xi^4 r_\Sigma^3 D_p(z)\left(h_2\left(\frac{\xi}{D_p(z)}\right)^{\theta_2}+\lambda_*\right)}{(z+1)^3}\right)$$

$$y = \left(-\frac{6M(z+1)D_p(z)^2\left(h_1\left(\frac{\xi}{D_p(z)}\right)^{\theta_1}+g_*\right)}{\xi^2 r_\Sigma}-\frac{\xi^2 r_\Sigma^2\left(h_2\left(\frac{\xi}{D_p(z)}\right)^{\theta_2}+\lambda_*\right)}{(z+1)^2 D_p(z)^2}+3\right)^{1/2}$$

Scaling as k=ξ/Ds

$$w_{DE}(z) = \frac{r_\Sigma}{v}\left[\sqrt{3}\, r_\Sigma^3\, \xi^4 \left(2\lambda_* + h_2(2+\theta_2)(\frac{\xi}{D_p(z)})^{\theta_2}\right) - 3\tilde{J} r_\Sigma^2 (1+z)\xi^4 [\lambda_* + h_2(\frac{\xi}{D_p(z)})^{\theta_2}]\, D_p(z) \right.$$
$$\left. - 6\sqrt{3} M (1+z)^3 \left(2g_* - h_1(-2+\theta_1)\left(\frac{\xi}{D_p(z)}\right)^{\theta_1}\right) D_p(z)^4\right]$$

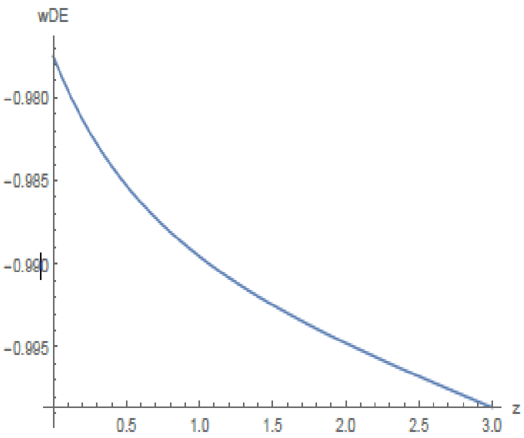
where

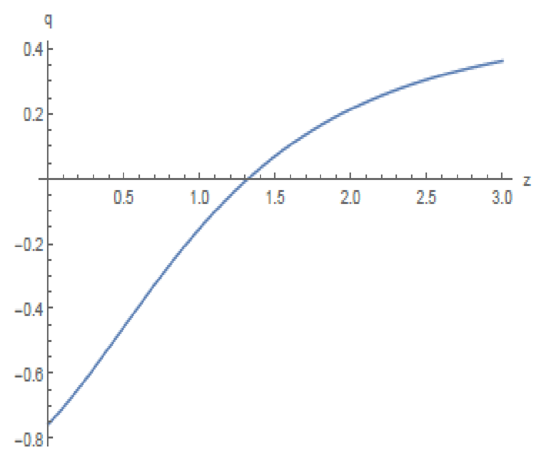
$$v = 3\, j\, (1+z)^4 \left[r_\Sigma^3 \xi^4 \left(\lambda_* + h_2(\frac{\xi}{D_p(z)})^{\theta_2}\right) D_p(z)/(1+z)^3 - 6 G_N M \xi^2 D_p(z)^3 + 6M\left(g_* + h_1(\frac{\xi}{D_p(z)})^{\theta_1}\right) D_p(z)^5 \right]$$

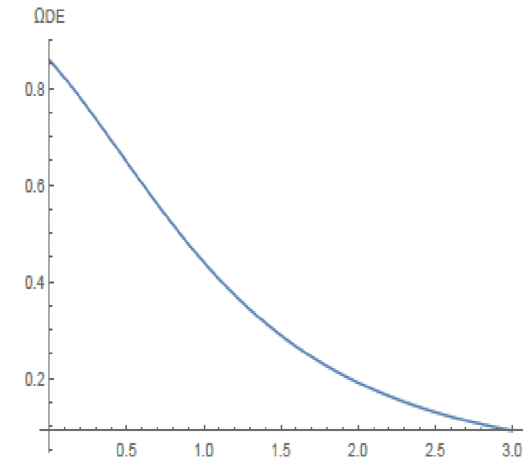
and

$$j = \sqrt{\left\{3 - \frac{r_\Sigma^2 \xi^2 [\lambda_* + h_2(\frac{\xi}{D_p(z)})^{\theta_2}]}{(1+z)^2 D_p(z)^2} - \frac{6M(1+z)[g_* + h_1(\frac{\xi}{D_p(z)})^{\theta_1}] D_p(z)^2}{r_\Sigma \xi^2}\right\}}$$

Scaling as k=ξ/Ds







the ratio of the cosmological constant force to the Newtonian force

For small clusters, this ratio is less than 1‰ either at the border or inside. For the largest possible clusters, the ratio becomes 20% at the border and less inside.

Similar results with all the above occur for clusters with different values of the parameters where most usually the extra force and potential are further suppressed.

Future work

- More thorough tests with observational data
- Extend the present study using Szekeres type swiss cheese models

Thank you

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END