Asymptotic Safety and Tensions in Cosmology

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Outline of the talk

I. Description of Asymptotic Safety framework for Quantum Gravity
II. Distinctive Phenomenology
III. Effect on Luminosity distances

I. Asymptotic Safety Paradigm for Quantum Gravity

Gravity

- Several attempts of quantum gravity try to address the description of gravity in the Ultraviolet and its interaction with other quantum fields

- String-branes theory / M theory
- Loop gravity
- Asymptotic Safety program (and similar non perturbative RG approaches)

UV-completion requires new physics:

- **String theory:**
  - unifies all forces of nature
  - Popular and well funded
  - requires: supersymmetry, extra dimensions
  - Problems with predictability
  - contains singularities

- **Loop QG - Spin foam models for quantum gravity:**
  - Discrete spectrum of quantum spacetime observables
  - keeps Einstein-Hilbert action as "fundamental"
  - new quantization scheme
  - 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 and extensions of it (with and without SM fields) can be

  a non-perturbatively renormalizable theory
- Not a complete framework
- Continuous spacetime
- 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 non-gaussian 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.

Gravity is a gauge theory

- This then raises the question of whether quantum gravity, though pertubatively non-renormalizable, might be asymptotically safe and meaningful after all. This motivation initiated the Asymptotic Safety, (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).

The problem

In Einstein's theory, the strength of the gravitational coupling is the number $g=G\,k^2$, 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, if G is constant.

The non-perturbative renormalization of Einstein's gravity in simple physical terms.

Perhaps the most illuminating discussion in this context has been presented by Polyakov, who noticed that as gravity is always attractive and therefore a larger cloud of virtual particles implies a stronger gravitational force, Newton's constant G should be anti-screened at small distances. The implication of this behaviour suggests that the dimensionless coupling constant tends to a finite non-zero limit at small distances

The non-perturbative renormalization of Einstein's gravity in simple physical terms.

A positive cosmological constant term is always repulsive therefore a larger cloud of virtual particles implies a less repulsive force, cosmological constant Λ should be larger at small distances. The implication of this behaviour suggests that the dimensionless coupling constant $\lambda = \Lambda k^{-2}$ tends to a finite non-zero limit at small distances

Solution

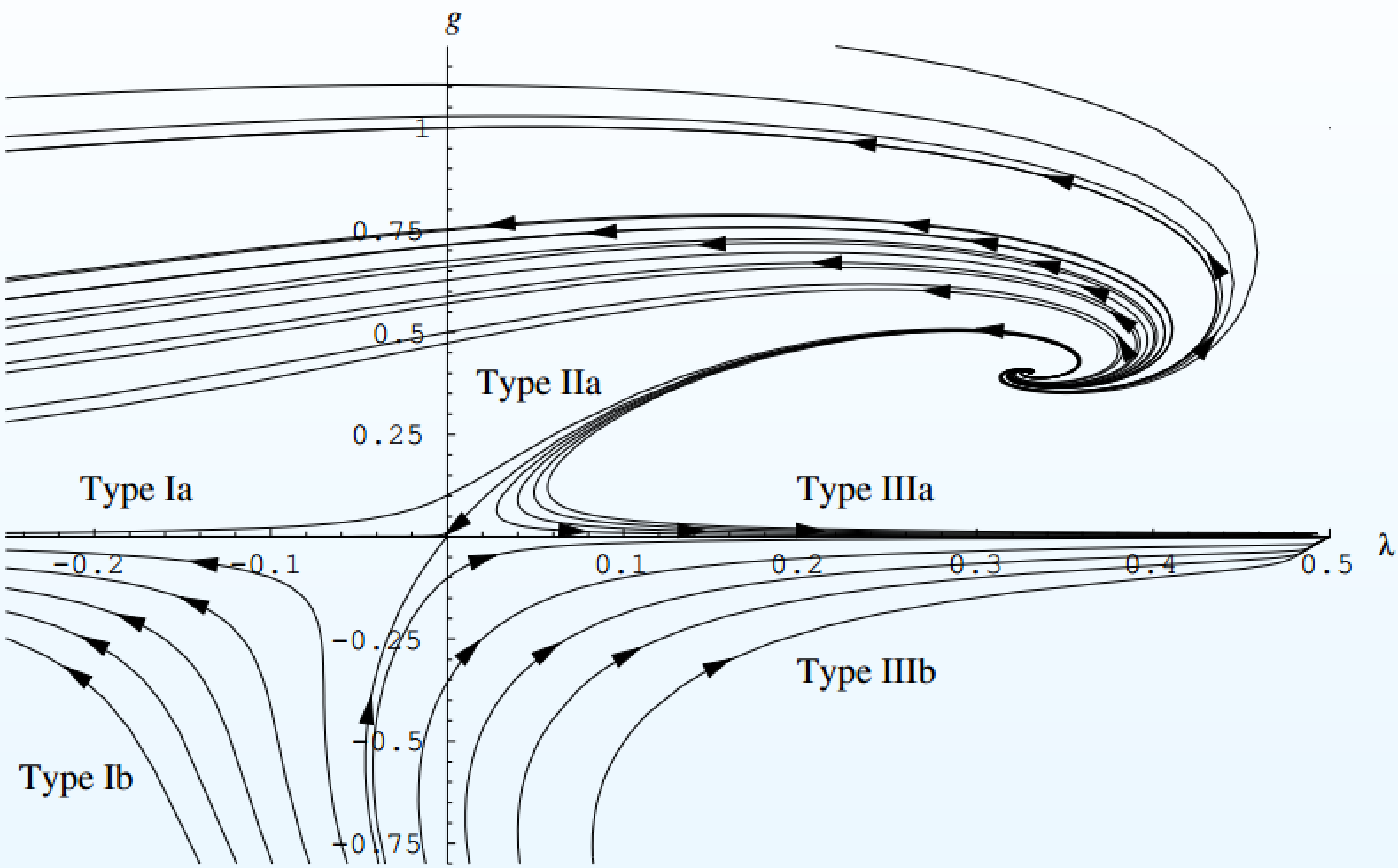
Newton's constant becomes a running coupling ***G(k)*** and it is conceivable (RG flow proof) that for large ***k*** it behaves like $\boldsymbol{k^{-2}}$ and $\boldsymbol{\Lambda(k)}$ behaves like $\boldsymbol{k^{2}}$, then *the dimensionless* **g** *and* $\boldsymbol{\lambda}$ would tend to a constant.
This is what is meant by a fixed point for Newton's constant and cosmological constant.

$$g = G\,k^2 \;, \qquad \lambda = \Lambda k^{-2}$$

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

Einstein-Hilbert-truncation: the phase diagram

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



II. Distinctive Phenomenology

Avoidance of singularities, Regular spherical solutions, BHs

- In the context of AS it is possible to find non singular cosmologies and non singular spherical solutions.
- *The existence of Λ that gets larger values at higher energies plays significant role.*
- Observational differences of these new type of solutions/spacetimes with the classical GR solutions could in principle be found with gravitational waves analysis or weak/strong lensing measurements.

Relevant papers

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

"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

"Effective field equations and scale-dependent couplings in gravity,"
A.Bonanno, G.Kofinas and V. Zarikas
Phys. Rev. D {103}, no.10, 104025 (2021)

Modified Einstein equations

$$\Lambda = \bar{\Lambda}\, e^{\psi} \quad and\; G = \bar{G}\, e^{\chi}$$

$$G_{\mu\nu} = -\bar{\Lambda}\, e^{\psi} g_{\mu\nu} - \frac{1}{2}\psi_{;\mu}\psi_{;\nu} - \frac{1}{4} g_{\mu\nu}\psi^{;\rho}\psi_{;\rho} + \psi_{;\mu;\nu} - g_{\mu\nu}\Box\psi + 8\pi G T_{\mu\nu}$$

with energy conservation given by

$$(GT_{\mu\nu})^{;\mu} + G\left(T_{\mu\nu} - \frac{1}{2} T g_{\mu\nu}\right)\psi^{;\mu} = 0$$

RG improved BHs

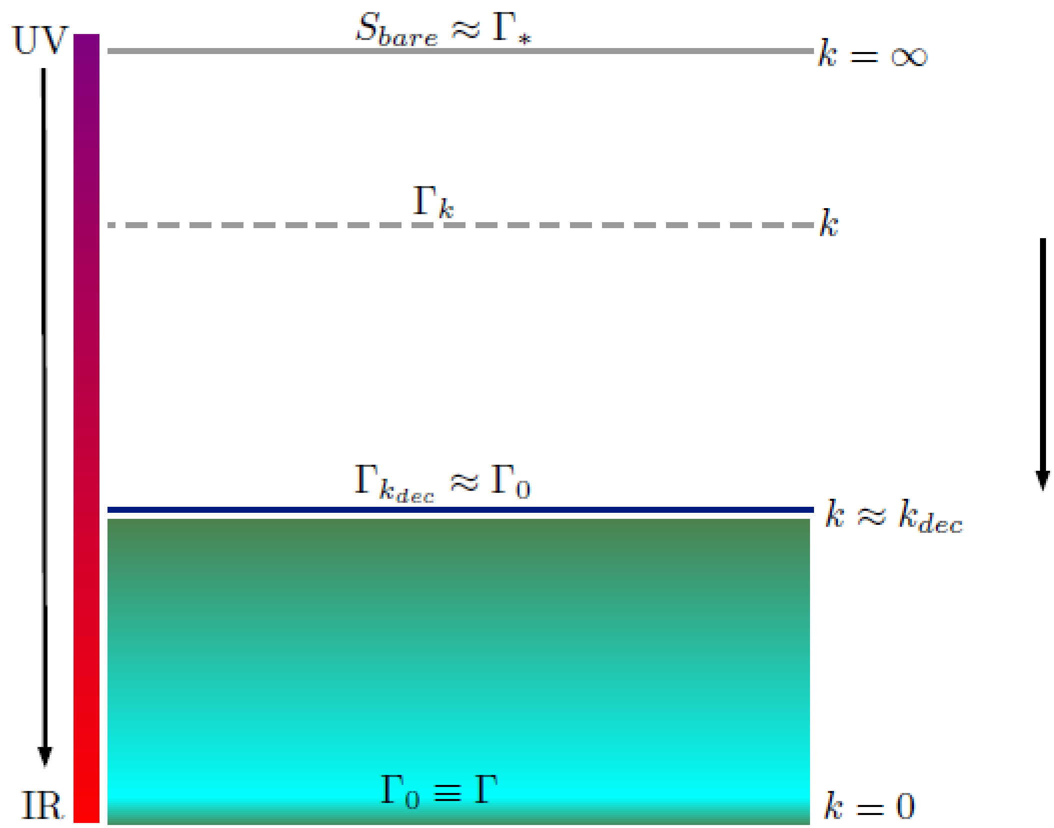
A. Adeifeoba, A. Eichhorn and A. Platania, Towards conditions for black-hole singularity-resolution in asymptotically safe quantum gravity, Class. Quant. Grav. 35 (2018) 225007 [1808.03472].

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

They do not process a singularity for some values of θ_1, θ_2

$$g_k = g_* + g_1\left(\frac{k}{M_{\mathrm{P}}}\right)^{-\theta_1} + g_2\left(\frac{k}{M_{\mathrm{P}}}\right)^{-\theta_2}$$

$$\lambda_k = \lambda_* + \lambda_1\left(\frac{k}{M_{\mathrm{P}}}\right)^{-\theta_1} + \lambda_2\left(\frac{k}{M_{\mathrm{P}}}\right)^{-\theta_2}$$



Collapse

- Non singular collapse in the context of AS have been studied in :

“Singularity-free gravitational collapse and asymptotic safety”

Ramón Torres (Barcelona, Polytechnic U.)

Phys.Lett.B 733 (2014), 21-24

“Dust collapse in asymptotic safety: a path to regular black holes”

Alfio Bonanno , Daniele Malafarina , Antonio Panassiti

e-Print: 2308.10890 [gr-qc]

Inflation

- There are several AS papers that claim the production of inflationary period
- Most recent study: Conformally reduced quadratic gravity was proved to exhibit a non gaussian fixed point ensuring UV completeness and at the same time including Starobinsky inflation.

«Ultraviolet behavior of conformally reduced quadratic gravity»
Alfio Maurizio Bonanno, Maria Conti, Sergio Luigi Cacciatori , e-Print: 2304.12011 [hep-th]

Recent cosmic acceleration (dark energy)

- A new swiss cheese model that matches a homogeneous and isotropic cosmological metric with the AS corrected Schwarzschild-de Sitter metric generates recent passage from deceleration to acceleration, without need for fine tuning and extra fields

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

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

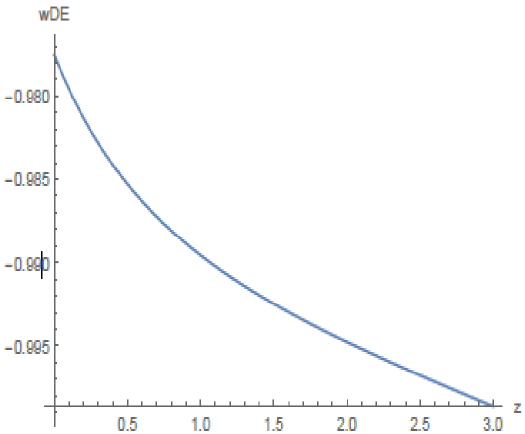
Two matching conditions

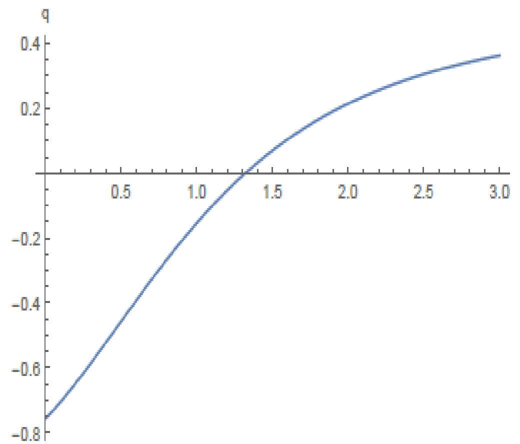
Let us consider a four-dimensional manifold M with metric $g_{\mu\nu}$ and a timelike hypersurface Σ which splits the spacetime M into two parts.

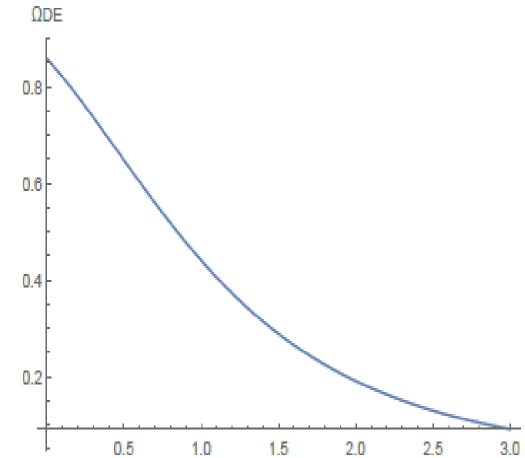
Continuity of the spacetime across the hypersurface Σ implies that h_{ij} (induced metric) is continuous on Σ, which means that h_{ij} is the same when computed on either side of Σ.

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.

Scaling as k=ξ/Ds







"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.

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

AS and Interacting dark energy

"Relieving the H0 tension with a new interacting dark energy model" Li-Yang Gao, Ze-Wei Zhao, She-Sheng Xue, Xin Zhang

Published in: JCAP 07 (2021), 005

They work with a scenario of vacuum energy interacting with matter and radiation. They modified ΛCDM to be compatible with AS theory, assuming

$$G/G_0 = (1+z)^{-\delta_G} \text{ and } \Lambda/\Lambda_0 = (1+z)^{\delta_\Lambda}$$

They study two models one with related G, Λ and one model with independent G, Λ. Both, relieving the *H0* tension and fitting to the current observational data.

III. AS and SNIa luminocity distances

“*Phenomenological footprints of Λ varying gravity theories inspired from quantum gravity models in the multi-messenger era*”

M.Good and V. Zarikas

Accepted in Classical and Quantum Gravity

Λ varying models

This part of the talk refers to models with varying CC but of a specific type. A varying cosmological constant, Λ(xi, t), may be a function of the physical characteristics of the system under consideration, like its spatial size or energy density.

This is realized in some existing interesting approaches to quantum gravity. It generates distinctive phenomenological consequences if the system under study is not the whole Universe but an astrophysical object like a cluster of galaxies or a black hole.

A way of observing these types of Λ varying models will be described

- RG flow methods to explore quantum gravity are still under development and require further elaboration.
- However, the proposal does not rely on details of the RG flow. The proposed phenomenological signature <u>assumes only a varying cosmological constant whose values are different if it refers to different astrophysical objects with different sizes and energy content</u>

Case I

- Perhaps this is the most expected case from the AS phenomenology point of view. Cosmic voids (low density systems) are associated with a negative or zero or negligible positive CC while regions of space with clusters of galaxies (higher densities) are associated with positive values of CC of the order of the value used for the ΛCDM model.
- The exact value of a CC, on the astrophysical scale, is not known

Case II

- Due to the absence of concrete IR quantum gravity corrections, it is useful to mention also another possibility that can be phenomenologically interesting.

- A reversed setup could be that now in low densities systems like voids, there is a positive CC of the order of the value that is compatible with the ΛCDM while in higher densities systems like regions of space with clusters of galaxies, we have either a negligible positive CC or a negative CC which may have a value that could contribute to the missing dark matter.

- Or it could be that there is a negligible positive or negligible negative CC in low-density systems like voids, while in higher densities systems like regions of space with clusters of galaxies, we have a negative cosmological constant that could contribute to the missing dark matter.

Luminocity distance

A simple way to model the astrophysical setup is to work with a different scale factor a(t) and consequently Hubble rate in the voids compared to the ones used for the regions of space with matter due to the local spatial variations of CC. Of course, this is a simple model, and a fully inhomogeneous treatment is needed.

$$D_L = -(1+z)\int_{t_0}^{t_{emit}} \frac{dt}{a(t)} = -(1+z)\int_a^1 \frac{da}{a^2\,H(a)} = (1+z)\int_0^z \frac{dz'}{H(z')}$$

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Simple scenario

Let us suppose we have a path that initially begins from a distant cluster region after passing from a void and after coming into our cluster region; then, the integral will be split into three parts where the Hubble rate will be different. Then, the total luminosity distance is

$$
\begin{aligned}
D_L &= \frac{a_0}{a_{vf}} \int_0^{Zvf} \frac{dz'}{H_c} + \frac{a_{vf}}{a_{vi}} \int_{Zvf}^{Zvi} \frac{dz'}{H_v} + \frac{a_{vi}}{a_{emit}} \int_{Zvi}^{Z} \frac{dz'}{H_c}, \\
&= (1+z_{vf}) \int_0^{Zvf} \frac{dz'}{H_c} + \frac{1+z_{vi}}{1+z_{vf}} \int_{Zvf}^{Zvi} \frac{dz'}{H_v} + \frac{1+z}{1+z_{vi}} \int_{Zvi}^{Z} \frac{dz'}{H_c}
\end{aligned}
$$

where zvi, zvf , z the redshifts at the first entrance of the signal into the void, the redshift of the signal at the exit from the void, and the redshift of the source respectively

- Now, in the case the signal passes from N voids and M clusters/filaments, the luminosity distance is

$$D_L = (1+z_{vf\,N})\int_0^{Zvf\,N}\frac{dz'}{H_c} + \sum_p \frac{1+z_{vi\,p}}{1+z_{vf\,p}}\int_{Z_vf\,p}^{Zvi\,p}\frac{dz'}{H_v} +$$

$$+\sum_q \frac{1+z_{ci\,q}}{1+z_{cf\,q}}\int_{Z_cf\,q}^{Zci\,q}\frac{dz'}{H_c} + \frac{1+z}{1+z_{vi\,1}}\int_{Zvi\,1}^{Z}\frac{dz'}{H_c}$$

Test

- Construct one sample with signals whose line of sight contains much more voids than the second sample of signals. Then we have to find statistical differences in the mean of Λ

Under-densities and over-densities approach

Suppose we get signals from a sample (sample 1) of astrophysical sources that arrive on earth passing from an under-dense cosmic region. Let us assume that this region has an average matter density given by ρ_1. Then, a second sample should be determined with signals passing regions with over-density i.e., with an average matter density given by ρ_2. Then

$$D_{Li} = (1+z)\int_0^z \frac{dz'}{H_i(z')},$$

$$H_i^2 = H_0^2\left[\Omega_M\,(1+z)^3 + \frac{\Lambda_i}{3H_0^2} + \Omega_k\,(1+z)^2\right]$$

Asymptotic Safety

This test would be an important indication of AS or similar RG approaches to quantum gravity

$$\Lambda_i = \xi\, \rho_i^{1/2}.$$

$$\frac{\Lambda_1}{\Lambda_2} = \frac{\rho_1^{1/2}}{\rho_2^{1/2}} = \frac{\epsilon_1^{1/2}}{\epsilon_2^{1/2}}$$

Future work

- Simulations and comparison with observational data

- Extend the present study using Szekeres type models

Thank you

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END