Fixing Cosmological Constant on the Event Horizon

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WORLD IS RULED BY DARK FORCES

Main aspect of the cosmological constant problem follows from the assumptions that the energy density generated by vacuum fluctuations depends quartically on a cutoff at the Planck scale.

A very simple solution to this problem is given in models where Λ appears as an integration constant unrelated to any parameters in the Lagrangian (e.g. Unimodular and Thermodynamic gravities).

This change of the role of Λ does not solve the problem completely, but changes it from a question of fine-tuning to a choice of boundary conditions.

Buchmuller & Dragon, *JHEP* **08** (2022) 167

Unimodular Gravity

In **Unimodular Model** (a gauge fixed version of **GR**) the determinant of the metric is not subjected to variation:

$$\delta\sqrt{-g}/\delta g_{\mu\nu} = 0 \, .$$

The term coming from the variation of $\sqrt{-g}$ is missing in standard variation equation and for the rest terms we have

$$\nabla^{\nu}\left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - 8\pi G \, T_{\mu\nu}\right) = 0 \, .$$

Then, in equations of the model appears an integration constant Λ,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + g_{\mu\nu}\Lambda\right) .$$

The **Unimodular Gravity** is locally indistinguishable from classical **GR**, the difference is that Λ is a constant of integration, rather than a coupling constant.

Henneaux & Teitelboim, *Phys. Lett.* **B 222** (1989) 195;
Jack Ng & van Dam, *J. Math. Phys.* **32** (1991) 1337

Thermodynamic Gravity

Within the **Thermodynamic** model **Einstein**‘s equations can be written similar to the **First Law of Thermodynamics**:

$$\left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R\right) u^\mu u^\nu = 8\pi G\, T_{\mu\nu} u^\mu u^\nu .$$

For ideal fluids the classical **Gibbs–Duhem** relation gives

$$T_{\mu\nu} u^\mu u^\nu \quad \rightarrow \quad \rho + p = \frac{T S_m}{V} .$$

If u^ν is the orthogonal to the observer’s horizon null vector field,

$$g_{\mu\nu}\, u^\mu u^\nu = 0 ,$$

in tensorial **Einstein**’s equations,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + g_{\mu\nu} \Lambda\right) ,$$

Λ arises as an integration constant.

Jacobson, *Phys. Rev. Lett.* **75** (1995) 1260;
Padmanabhan, *Rept. Prog. Phys.* **73** (2010) 046901.

Info-Geometry

The key ingredient in the statistical description is entropy S, which allows to model physical systems using universal framework. Nature is built by information, even geometry is a construction of an observer. Locations of quantum particles have no meaning and one needs entropy labeled by some informational coordinates x^i.

Total action of the Universe of N particles $\sim N^3\hbar$ and $S_U \sim log\, N^3 = 3\, log\, N$. On the other hand, the entropy of a random variable is $log\, N$. So, an observer obtains 3 copies of $S \sim log\, N$, which is used to define information distances. Then, one needs the three information coordinates, x^i $(i = 1, 2, 3)$.

An observer associates S with a volume of the radius, $R^2 = g_{ij}x^i x^j \sim S(x^i)$ (**Bekenstein** bound) in the center of which probability distribution is maximal. The information distance between two distributions is given by the variance

$$dl^2 = g_{ij}dx^i dx^j. \qquad \text{(Fisher-Rao information metric)}$$

This **Riemannian** metric (distinguishability) represents observer's knowledge. Uncertainty grows with volume, e.g. $S_{BH} = \pi r_s{}^2/G$ is proportional to the area of the black hole's horizon $r_s = 2GM_{BH}$.

Caticha, *Entropy* **17** (2015) 6110;
Gogberashvili, *Int. J. Theor. Phys.* **55** (2016) 4185

Informational Special Relativity

In the **World Ensemble** picture all entangled particles define a fundamental frame. This model universe is homogeneous and isotropic. For ‘inertial’ observers, having the same informational entropy, the universe looks similar. The local relativistic invariance is a fictitious symmetry, disappears for cosmological scales.

The ***Special Relativity*** axioms in information terms:

(A) Principle of informational entropy universality: The laws of physics have the same form for the observers with the same information, but different constant thermodynamic and entanglement entropies;

(B) Principle of finiteness of information density (**Bekenstein** bound): A finite volume of space can only contain a finite amount of information.

For a finite world ensemble there is a limit to how fast information can move through and ***c*** can be understood as the information velocity (the entanglement tsunami), which measures the response time of the universe on the transfer of ***1 bit*** of information, i.e. exchange of one particle.

Gogberashvili, *Found. Phys.* **52** (2022) 74

Algebraical Entropy

Basic microscopic laws are time reversible. In non-associative cases, algebraical entropy leads to t-asymmetry - forward and backward probabilities are not equal.

Polar form of an octonion: $X = N\alpha$ ($N = XX^* = X_0^2 + X_n^2$). The unit octonions, $\alpha = e^{j\theta}$ (j is the unit 7-vector), are used to define $SO(7)$ rotations (21 angles in $(-\pi, \pi]$, distribution function $f(x|N) = 1/(2\pi)^{21}$). The differential entropy,

$$H(\theta|N) = -\int dx^{21}\, f(x|N)\, \log_2 f(x|N) = 21 \log_2(2\pi)\ bit$$

is variant under change of variables and one needs **Kullback–Leibler** divergence:

$$D(f||g) = \int dx\, f(x)\, \log_2 f(x)/g(x)\ .$$

We compare the angles distribution of passive rotations that preserve norms $g(x|N) \to SO(7)$ (21 angles), with one for active transformations, $f(x,N) \to G_2$ (14 angles)

$$D(f||g) = (21 - 14)\, \log_2(2\pi) \approx 18.6\ bit\ .$$

This unavoidable in a measurement algebraical entropy can determine the arrow of time, as thermodynamic entropy does.

Gogberashvili, *Entropy* **24** (2022) 1522

Entropy Neutrality

3rd **law:** **For a isolated system (Universe) total entropy is zero -** $S + I + \varepsilon = 0$

$S = \ln N$ (**Boltzmann**'s statistical entropy)

$I = -\sum_{i=1}^{N} p_i \ln p_i$ (**Shannon**'s information entropy)

$\varepsilon = \Sigma_{tot} - \Sigma_{sub}$ (Entanglement entropy)

$\Sigma = -tr(\sigma \ln \sigma)$ **von Neumann**'s entropy (σ – density matrix).

$S = I$, if $p_i = 1/N$. Usually $I \geq \varepsilon$, equality holds for orthogonal σ-s.

Information corresponds to action $\sim A/\hbar$ (Generalized **Landauer**'s principle). Entropy neutrality → Information quantization: $A_{min} = \hbar$. A measurement, even a thought experiment, is accompanied by the transfer of at least one quanta $\hbar$.

Conserved quantity is S_{tot}, not E_{tot}. To restore E_{tot} conservation we need E_{inf}.

For an observation in which *1 bit* of entanglement information is lost the energy that must be emitted into the vacuum is $k_B T_{CMB} \ln 2 = 1.6 \times 10^{-13}\ GeV$.

Entanglement energy is missed in standard formalism and can be accounted for by a Λ-like boundary term.

Gogberashvili, *Int. J. Theor. Phys.* **55** (2016) 4185;
Gogberashvili & Modrekiladze, *Int. J. Theor. Phys.* **61** (2022) 149

Meaning of Boltzmann's Constant

Boltzmann's constant k_B always appears together with the temperature T. So, it is natural to relate k_B with T (instead of the thermodynamic entropy S) and introduce the dimensionless **Shannon**'s type statistical entropy for atoms $S \rightarrow S/k_B$.

Only the atomic scale is relevant for thermodynamics, there are no smaller particles, which can be used to build solid structures. Quantum properties restrict classical considerations of subatomic physics and disappear for large scales, but still enable creation of ensembles of quasi-classical particles.

Characteristic energy that dictates the value of the unit of T is the thermal energy of a simplest atom (hydrogen). Hydrogen can be treated as a sphere of **Rydberg** radius $r \simeq 10^{-7}\ m$ that vibrate under the force between p^+ and e^-. Vibrational frequency appears to be in far-Infrared range: $\omega \simeq 4 \times 10^{11}\ s^{-1}$.

$T = 0$ corresponds to the vacuum ($n = 0$) of the quasi-classical oscillator: $E_n = (n + 1/2)\omega\hbar$. The unit of thermal energy of **3**-oscillator: $k_B T_0 = \omega\hbar/3$. For $T_0 = 1\ K$ this explains the numerical value of **Boltzmann**'s constant: $k_B = 1.4 \times 10^{-23}\ J/K$.

Gogberashvili, *Mod. Phys. Lett.* **B 33** (2021) 2150235

Entropy Balance for M87

For black holes $I \to 0$ and $S_{BH} + \varepsilon_{BH} = 0$, information contributes to entanglement (the effect is stronger close the horizon). Potential energy stored in entanglements should be negative. We model this dark-energy-like behavior by effective Λ that imitates the acceleration of space-time. The radial velocity of matter: $v_r \sim 1 - r_s/r + r^2 \Lambda/3$ and one observes apparent superluminal motion at horizon if $\Lambda > 3r_s/r^3$.

For $M_{BH}(M87) \sim 1.3\times10^{40}$ kg superluminal motion observed for two knots, e.g. $v_{HST-1} \sim 6.3\ c$, $d_{HST-1} \sim 80$ pc, $M_{HST-1} = \rho V_{HST-1}$ (where $\rho \sim 10^{-17}$ kg/m^3 is the energy density in the center of *M87*).

Bekenstein's entropy: $S_{BH}(M87) \sim \pi r_s^2/L_{Pl}^2 \sim 10^{96} \sim - \varepsilon_{BH}$. The portion of the knot entanglement entropy: $\varepsilon_{HST-1} = - \varepsilon_{BH} M_{HST-1}/E \sim -10^{25}\ V_{HST-1}\ m^{-3}$, where $E \sim 10^{54}$ kg denotes the energy in the black holes creation zone $\sim 10^4$ Mpc.

This effective cosmological constant $\Lambda_{HST-1} \sim 10^{-41}\ m^{-2} \sim 3r_s/d^3{}_{HST-1}$ can explain the apparent superluminal motions of knots close to the black hole in **M87**.

Gogberashvili & Modrekiladze, *Int. J. Theor. Phys.* **61** (2022) 149

Entropy Balance for the Universe

1. $H^2 = \frac{8\pi G}{3}\rho + \frac{1}{3}\Lambda$ (**Friedmann** equation)
2. $\dot{H} + H^2 \equiv \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3\,p) + \frac{1}{3}\Lambda$ (Acceleration equation)

Equivalent system without cosmological term:

1. $\dot{H} = -\,4\pi G(\rho + p)$ (Obtaining by subtracting **1.** from **2.**)
2. $\dot{\rho} = -\,3H(\rho + p)$ (Energy-momentum conservation $\partial_\nu T^{\nu\mu} = 0$)

Integration of **1+2** gives **Friedmann**'s equation **1** with an integration constant $C = \Lambda/3$. So Λ can be a free parameter, from observations $\Omega_\Lambda = \Lambda/3H_0^2 \approx 0.69$.

Holographic relations for the **Hubble** sphere $R_H = 1/H$ ($Area = 4\pi R_H^2$),

$$S = Area/4G; \qquad \rho + p = TS_m/V; \qquad T = 1/2\pi R_H.$$

Entropy balance $\dot{S} = S_m Area$, leads to **1**: $S = \pi(1 - \Omega_m)/CG$. Matter fields should be limited by $R_e \approx 0.96 R_H/\sqrt{\Omega_\Lambda}$. At the event horizon $\Omega_m \to 0$ and $C = 1/R_e^2$. Then, for the dark energy density we obtain the observable value:

$$\Omega_\Lambda \approx \frac{C}{H^2} = \frac{R_H^2}{R_e^2}.$$

Gogberashvili & Modrekiladze, *Int. J. Theor. Phys.* **61** (2022) 149;
Gogberashvili, *Adv. High Energy Phys.* **2018** (2018) 3702498;
Gogberashvili & **Chutkerashvil,** *Theor. Phys.* **2** (2017) 163

Conclusions:

- **We attempt to describe the universe in terms of informational quantities. The main dynamical principle - Conservation of the sum of all kinds of entropies: Thermodynamic, Quantum and Informational;**
- **Postulates of *Special Relativity* are re-formulated as the principles of the Entropy Universality and Finiteness of Information Density;**
- **The time-arrow can be connected with non-associativity. For octonionic functions any measurement generates 18.6 bit Algebraical Entropy.**
- **The vibrational energy of a hydrogen atom of the Rydberg radius, dictates to the value of Boltzmann's constant.**
- **The model can be used to explain observed superluminal motion close to the super-massive black hole of M87.**
- **In Friedmann's equation the cosmological term appears as an integration constant. Setting boundary conditions on the event horizon we obtain the observed value for the dark energy density.**

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7. **“Cosmological Constant in the Thermodynamic Models of Gravity”**
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