Journal of High Energy Physics, Gravitation and Cosmology, 2023, 9, 917-940
https://www.scirp.org/journal/jhepgc
ISSN Online: 2380-4335
ISSN Print: 2380-4327

A General Relativistic Approach for Non-Perturbative QCD

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How to cite this paper: Raut, U. (2023) A General Relativistic Approach for Non-Perturbative QCD. *Journal of High Energy Physics, Gravitation and Cosmology*, **9**, 917-940.
https://doi.org/10.4236/jhepgc.2023.94069

Received: March 21, 2023
Accepted: September 11, 2023
Published: September 14, 2023

Abstract

The formation of mini black holes is now considered to be a well-established and inescapable consequence of TeV scale particle collision scenarios in extra-dimensional/ADD models. Further, such mini black holes have been predicted to be produced at prodigious rates, of several thousand per year. Therefore, the continued null results from detector searches so far, including the most recent LHC runs of $\sqrt{s} = 14$ TeV, seem to suggest that new ideas may be critical for further advances in high energy physics. In this manuscript, we use a geometrical algorithm, inspired by general relativity, in particular Kerr-Newman de-Sitter black holes, to explore the non-perturbative (infra-red) sector of QCD. This has led us to a novel and more refined search criteria for LHC data compared to previous methods. We also explain why the current search has yielded null results. Our predictions are readily testable at detector sites. More importantly, our approach provides promising solutions to several long-standing problems, such as the hierarchy problem, problems with the continued failed attempts to integrate gravity into the standard model, and finally quark confinement.

Keywords

General Relativity, Hierarchy Problem, LHC Phenomenology, New Black Hole Search, Gravitational Waves

1. Introduction

1.1. A Radical New Idea Is Needed

It is generally recognized today that the non-perturbative (infra-red) sector of QCD remains a notoriously intractable problem in theoretical physics. This follows several decades of intense effort using every available tool, including lattice QCD, extra/warped-dimensional theories, supersymmetry, gauge/gravity duality methods such as AdS/CFT, etc.

Unfortunately, so far, the data collected from the ATLAS collaboration detectors do not seem to vindicate current gauge-gravity or supersymmetric approaches [1]. Black-hole searches at LHC have also so far yielded null results [2], thereby questioning the hypothesis of extra/warped dimensions of space-time.

In this work, we attempt to gain fresh insight into this challenging issue by using geometrical methods based on general relativity. Such a venture is admittedly far more complicated in the prevalent physics climate, where there seems to be a growing chasm between the way physics is understood by general relativists versus how it is understood by particle physicists. A real communication between the two sides is lacking, further exacerbating the status quo. We partly address this concern in this manuscript by embracing a departure from conventional methods. Instead of the usual string-inspired AdS/CFT gravity-gauge duality, we use a different type of gauge/gravity duality based on a geometrical algorithm first introduced in [3] [4], and successfully developed over the years by several other authors [5]-[13].

1.2. Color Confinement vs. Gravitational confinement

The well-known property of color confinement in QCD essentially forbids the existence of isolated quarks and gluons in the physical vacuum, dooming them to be forever confined to the inside of the hadrons.

Apparently, the only other known situation where one can encounter this kind of confinement is the well-known gravitational confinement provided by black holes.

Based on this, some authors have recently been prompted to draw up an analogy between the two situations and therefore theorize that there should be a color version of event horizon, just like its gravitational counterpart [14] [15] [16].

This leads to the important conjecture that color confinement could lead to a dual description of the strong interactions in terms of the usual gravitational confinement of matter inside black holes. So, we basically have two descriptions for the confinement of quarks inside hadrons that are dual to each other, a geometrical description in terms of a curved space-time background, and the other description based on usual QCD principles. We will refer to this conjectured gauge-gravity duality as the "geometrical dual approach" or GDA in the remainder of this manuscript.

1.3. A Geometric Version of Double Copy Formalism

All such geometrical methods seemingly have their roots in a pre-cursor of the "double copy procedure" recently made popular, which simply states that at a perturbative level, one can construct a gravitational amplitude from a product of two gauge theory amplitudes. How widely applicable the double copy procedure is, has not been resolved, but it seems to apply in several situations. What we do know is that it is a general method for obtaining gravitational field solutions in a non-Abelian gauge theory, starting from gauge solutions. Therefore, gravity solutions should be obtainable from the color QCD solutions.

The double copy was already inherent in the earlier work of Kawai, Lleweyn and Tye, (KLT) [17], who had shown us back in 1986 that any tree level closed string amplitude (like the ones representing gravitational interactions) could be expressed as some kind of a product of two open string amplitudes, such as those describing gauge interactions. The more recently discovered BCJ double copy procedure [18] is actually also a form of geometric gauge/gravity duality and is different from the string-inspired AdS/CFT gravity-gauge duality [19].

As shown below, in the geometric approach of Ne'eman *et al.* [11] [12], they drew attention to the interesting fact that rather than an effective weak Newtonian gravity, an "effective strong gravity" is what seems to emerge in a natural manner in the IR region of QCD. They had also established early on that the strong gravity field actually is a double copy of the gluon field. A similar argument is given in [20].

In particular, using a Stelle-type [21] of quadratic Lagrangian that described the internal curved space of hadrons, they were able to show that the IR sector of QCD is dominated by dressed two or more gluon exchanges in QCD leading to phenomena such as diffeomorphism invariance, and the occurrence of Regge excitations, which are basically families of resonance states that display rising Regge trajectories, as well as other hadronic features that mimic gravity, indicating that *gravity or an effective gravity-type force must necessarily emerge in the IR limit*.

More precisely stated, the IR region of QCD can be approximated by the exchange of a dressed two-gluon field: $G_{\mu\nu} = B^a_\mu B^b_\nu \eta_{ab}$, where B^a_μ is the color gluon gauge field, and η_{ab} is the color Cartan-Killing metric. μ and ν are the usual space-time indices and take on values from 1 to 3. The main point to note is that any set of colorless many-gluon exchanges must also include a gravity component.

The claim we make here is that this double copy feature should arise in all geometric approaches to QCD, regardless of the actual details of the method used. This means that the strong (nuclear) force of gravity arises naturally in the non-perturbative limit can also be approximated by a two-gluon field. This leads to a new version of the gauge/gravity duality.

1.4. GDA with De-Sitter vs. Anti-de-Sitter Space

In this manuscript, we use this GDA analogy in the context in which it was originally put forth [6] [7] [8] [9], where the elementary particles are assumed to be Kerr-Newman "strong gravity" black holes, in the interiors of which gravity assumes a very high value. We retain the "enormous" value of gravity.

Although this original thread has also been extended in recent years to anti de-Sitter black holes [22], we are going to focus on de-Sitter black holes. This choice is also consistent with recent observations of supernova [23], which strongly suggest that a de Sitter universe with a positive cosmological constant might be very relevant to our current understanding of the universe.

The plan of the paper is as follows: In Section 2, we re-examine the hierarchy problem, and make a crucial case for not ignoring a possible role of gravity in the micro-world.

In Section 3, we introduce the basic de Sitter class of spacetimes, and discuss how hadrons can be modeled as Kerr-Newman de Sitter black holes.

In Section 4, we apply the GDA to the dynamics of heavy-ion collisions, and finally put forth our novel hypothesis, based on the geometrical algorithm discussed in the first three sections. We also try to show why current searches for mini-black holes and other TeV scale phenomenological signatures have not met with success at accelerator sites.

In Section 5, we discuss possible phenomenological signatures and consequences of the geometrical dual approach and suggest how such a geometrical approach to QCD can be experimentally tested with already existing or planned equipment, such that it can either be completely justified or falsified.

In Section 6, we present a discussion and analysis of our proposed hypothesis, followed in Section 7 by concluding remarks. We also look at the exciting possibilities ahead.

2. Methodology

2.1. Introducing Gravity in the Micro-World

Soon after his General Theory of Relativity was published, Albert Einstein posed the following question (in German) in a 1919 manuscript: “Do gravitational fields play an essential role in the structure of elementary particles?” [24]. He was known to always answer this in the affirmative by stating: “There are reasons to believe that the structure and formation of elementary particles are gravitational in Nature.” In fact, both Riemann, as well as Einstein endorsed the idea that elementary particles were just intensely curved local regions of spacetime.

However, even after several decades of intensive research, Einstein’s question remains without any answer, and gravity has still not been meaningfully integrated into the Standard Model.

The fact that gravity is highly non-renormalizable, has led to the unfortunate situation where it is deemed more convenient to simply ignore the gravitational force completely when dealing with the interactions of elementary particles, the oft-quoted justification being: “because of the weakness of the gravitational interactions compared to the other three fundamental forces…”. This statement of course seriously lacks content, because there is no way to actually compare the interactions in a meaningful way. To quote Wilzek: “The question is not ‘why is gravity so weak’; the real question is: “why is the electron mass so small?” Another way of putting it would be “Why is the Plank mass so huge relative to the Standard Model scale? Or why is the Higgs only 125 GeV?” These kinds of concerns are generally different versions of the "Hierarchy" problem, which despite our best efforts has defied any solution to date.

A key component of our method is that instead of positing extra warped dimensions of space, we introduce a very large value for G inside hadronic particles. It must be noted that to date no-one has been able to determine the actual value of the gravitational coupling constant G in the subatomic domain, in particular inside strongly interacting particles.

After all, it must be remembered that the gravitational coupling constant depends on the energy involved. This is in sharp contrast to the electromagnetic coupling constant (which remains at 1/137) at all energies! Thus, the gravitational constant would become larger at smaller distance scales, and at the Plank scale it is expected to become as strong as the strong coupling!

2.2. Large G and Quark Confinement

We use Einstein's General Relativistic equations for hadronic matter, since in our scenario, hadrons are simply scaled down versions of the Universe, with a value of $G \sim 10^{38}\ G_N$. For example, protons could then be considered to be "nuclear-sized" black hole of the strong gravitational type. This point of view is also referred to as nuclear or particle-level gravity by various authors.

To clarify this point, consider a typical hadron of mass ~ 1 GeV.

For it to be a Schwarzschild-style black hole, its radius would be given by:

$$R_s = 2GM\ . \tag{2.1}$$

With the usual Newtonian value of G, R_s can be calculated to be roughly equal to:

$$R_s \cong 1.27\times 10^{-38}\ \text{GeV}^{-1} \tag{2.2}$$

Expressed in units of fermi, $R_s \cong 3\times 10^{-39}\ \text{fm}$, *i.e.*, about 10^{-39} times smaller than the radius of a typical hadron, assuming the latter has a radius of $R \sim 1$ fm.

So, it is of some curiosity to note that in order to make a black hole out of a typical hadron, the mass of the hadron would have to be squeezed into a volume of $\left(\frac{1}{2.7\times 10^{-39}}\right)^3$, or ~ 10^{120} times as small as the usual hadronic volume! (See also [25] for a similar conclusion).

However, if one could raise the interaction strength in the hadron from the gravitation to the strong force, we would then define the "strong" hadron, with a "strong Schwarzschild radius" given by:

$$R_s^h = 2\frac{\alpha_s}{GM^2}R_s \tag{2.3}$$

$$\text{or}\quad R_s^h = 2\frac{\alpha_s}{M} \tag{2.4}$$

$$\text{which gives}\quad R_s^h \sim 1.2\ \text{fm} \tag{2.5}$$

implying that the hadron has a "strong" Schwarzschild radius equal to its confinement radius!

This leads to the very interesting possibility that the confinement of quarks in the hadron can be looked at as the "strong interaction" version of the usual gravitational confinement of matter in black holes.

3. Hadrons as Black Holes of Color Confinement

3.1. Strongly Interacting Particles as Color Black Holes

We will assume in this work that all strongly interacting particles (hadrons) behave like color black holes, that is to say, not black holes of the gravitational charge, but rather black holes of the "color" charge.

For example, one obvious difference between the gravitational black hole, and the "color" black hole is the fact that the interaction which dominates the usual black hole is the universal gravitation of Newton. *In contrast, in the case of the "color" black hole a "strong" induced gravity appears. This is not the usual Newtonian gravity, but a strong version that dominates the IR segment of QCD*, sometimes referred to as a "strong chromo-gravity". This interaction is not only responsible for color confinement but occurs only in the curved intra-hadronic spacetime of hadrons and would just reduce to the usual Newtonian gravity outside the boundary of the hadrons. The radius of these strong black holes is ~ 1 fm, *i.e.*, just the radius of the hadron.

3.2. Mathematical Formalism

Following the original thread of [6] [7] [8] [9], the key idea is that physical laws are not only covariant under general co-ordinate transformations, but in addition are covariant under global discrete dilations.

$$x'_\mu = \rho x_\mu \tag{3.1}$$

where x_μ represents the co-ordinate system (t; x, y, z), $\mu = 0, 1, 2, 3$, and ρ can only have discrete values.

The usual Einstein-Maxwell equations, applicable to our cosmos, with a cosmological constant can be written as:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{3.2}$$

$$\text{where } T_{\mu\nu} = \frac{1}{4\pi}\left(F_{\mu\sigma} F_\nu^\sigma - \frac{1}{4} F_{\lambda\rho} F^{\lambda\rho} g_{\mu\nu} \right), \tag{3.3}$$

and Λ is the cosmological constant, assumed to be positive here).

These will also be the equations that will be used to describe the interior of the hadron as well,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda_h g_{\mu\nu} = \frac{8\pi G_h}{c^4} T_{\mu\nu} \tag{3.4}$$

with the difference being that we replace Λ with Λ_h and G with G_h where Λ_h and G_h are respectively the values that are taken on by Λ and G inside the hadronic particles.

Note the usual values of G and Λ in the regular Einstein equations, describing our cosmos, are given by the standard measured values:

$$G_N \approx 6.7\times 10^{-11}\ \mathrm{N}\cdot\mathrm{m}^2/\mathrm{kg}^2 \quad \text{and} \quad \Lambda_N \approx 10^{-52}\ \mathrm{m}^{-2} \tag{3.5}$$

in standard S.I. units, where G_N is the usual Newtonian constant of gravitation, and Λ_N is the usual cosmological constant. Mathematically, (3.1) and (3.4) must imply dilatation covariance.

Inside the hadron, we adopt Einstein-type equations with explicit understanding that the gravitational constant is now scaled up to a value of $G_h \sim \frac{hc}{m_\pi^2}$, and the usual cosmological constant will be replaced by the hadronic or "strong" cosmological constant of $\Lambda_h \cong 10^{30}\ \mathrm{m}^{-2}$.

3.3. Ultra-Relativistic Collisions Using KNdS Black Holes

Our framework to analyze the ultra-relativistic heavy-ion collisions will be most appropriate in that region of the $\ln(1/x)$ vs $\ln(Q^2)$ plane where the Froissart bound [26] is saturated to begin with, and the conventional parton picture breaks down to either the DGLAP [27] [28] [29] [30] or BFKL-type scenarios [31] [32].

In this context, it must be remembered that once parton saturation has taken over, the very concept of individual partons would not be valid, and any model using this concept is no longer viable. This was also investigated in the context of string theory (e.g. Polchinski and Strassler [33]), who could show that at large energies, parton-like behavior is not the dominant one, and the cross-section for strong gravitational effects, such as black holes begins to dominate, and finally take over the other processes.

This helps to argue the case for using colliding KNdS black holes to model high-energy collisions, since computing a total cross-section for hadronic scattering is inherently a non-perturbative process, and the main degrees of freedom should be the hadrons, rather than the individual partons.

We further argue that the QCD—induced strong effective gravity in the infra-red sector plays a key role in the dynamics of the collision. This role of gravity has been completely neglected in previous treatments.

It is also worth noting that perturbative treatments such as the CGC [34], fail to describe the large-x partonic degrees of freedom, since these modes are basically integrated out when the effective theory is built up. This leads to inconsistencies with what range of x-values would be permissible for the CGC to be valid.

4. New Paradigms for Hierarchy Problem and TeV Scale Gravity

4.1. Using a Large "G" for Hierarchy Problem

We would like to challenge the current paradigm of assuming extra/warped dimensions as a means of lowering the Plank scale. To solve the hierarchy problem the suggested traditional methods are to assume the existence of an arbitrary number of compact extra/warped dimensions [35] [36] [37]. This is supposed to lead to a modification of gravity at scales smaller than a millimeter. On the other hand, however, very little is known of the gravitational force at the higher energies involved in particle physics, and in fact the gravitational force has only been measured in the ~ 0.01 cm range, and its properties are virtually unknown in the regime smaller than 1 mm or so!

The accepted value of the Plank energy in our 4-D space-time is for the Plank scale, given by the usual expression $E_p \cong \sqrt{\frac{hc^5}{G}}$, $E_p \approx 10^{19}\,\text{GeV}$, which is significantly higher than the electro-weak scale, which is typically in the TeV range, and therefore completely out or reach by any conceivable experiments. This situation is referred to as the hierarchy problem, and the suggested current paradigm for solving this problem is through the introduction of large extra or warped dimensions.

In this manuscript, we use our dual geometric approach to propose another solution, using the argument that gravitation itself takes on a large value inside strongly interacting particles. Rather than reduce the Plank scale by introducing ad-hoc extra dimensions (for which there is growing doubt about their existence per accelerator data), it is just as possible to introduce a large value of G in the expression for the Plank scale energy $E_p \cong \sqrt{\frac{hc^5}{G}}$, thereby giving us the expression:

$$E_p \cong \sqrt{\frac{hc^5}{G_h}} \quad (G \text{ is replaced by } G_h) \tag{4.1}$$

It is clear that if instead of the usual Newtonian value of $G_N = 6.7 \times 10^{-11}$ in S.I units, we use instead the strong nuclear strength gravitation, which as seen in Section 2 of this manuscript, is equal to $G_h = 10^{38} G_N$, this would significantly reduce the Plank scale, similar to introducing any kind of extra/warped dimensions of space-time.

Substituting all numerical values in the expression above, it turns out that the Plank scale is reduced to not the TeV range, but even lower, to the GeV range! There is currently no known argument that can forbid this scenario to be the one favored by Nature!

4.2. A TeV Scale Does Not Fix the Hierarchy Problem!

What remains unclear is why the TeV scale was chosen to solve the hierarchy problem in the first place. The main motivation was based on supersymmetry arguments, with the possibility of new physics appearing at the TeV scale, and the conjectured existence of TeV scale supersymmetry. Another reason is that for the Higgs mass to be 125 GeV, the supersymmetry breaking parameters would have to be at a minimum of the order of the TeV range. None of these arguments have been justified or validated.

On the contrary, several authors have shown [38] that the TeV paradigm seems, in actual fact to have created more problems than it has solved. Not only does it fail to address most of the on-going issues with the Standard model but it has actually created several more issues of its own, which are even worse. For example, as emphasized in [39], there are new problems caused by the flavor-changing neutral currents, and electric dipole moments from loops created with supersymmetric partners. There is also a huge problem with explaining why the supersymmetric Higgs/Higgsino mass squared parameter, μ, of the Standard Model in the expression $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d$ for the super potential term W_μ is comparable to supersymmetry breaking [40]. More recent speculation is that the 1974 GUT hypothesis is itself the starting point that led the high energy physics field into this quagmire.

As to whether a GeV scale for the Plank scale is feasible, it must be remembered that currently, there are huge, largely unresolved uncertainties due to model dependent and other free parameters, and therefore there is no agreed upon value of a minimal *grand unification scale*. Further, erroneous assumptions in the high energy community have led to the belief that signatures of new physics would definitely appear when the Plank scale is reduced to the TeV range, and further, if one went any lower, it is assumed there will be no distinct signatures, since we have not seen any.

That reasoning is flawed. As we will see in the next couple of sections, signatures of the GeV scale might already be very much present in current accelerator data, in the form of continuous creation of new hadrons. In fact, there has been a production of 59 new hadrons in currently available data. Ultra-relativistic collisions of the KNdS black holes would lead to production of larger hadronic black holes and their resonances, in accordance with Hawking's Area Law [41].

4.3. Hoop Conjecture and Feasibility of "Hadronic" Black Hole Production

Consider particle collisions with

$$E = 2\gamma m_0 c^2 > M_{Pl}. \tag{4.2}$$

Of course, one of the first things to consider should be whether ultra-relativistic two-particle scattering can theoretically produce a black hole in the first place, especially if the impact parameter is small.

A theoretical argument known as the "hoop conjecture", put forth by Kip Thorne [39] in 1972, imposes conditions under which a black hole can form. According to this conjecture, a black hole horizon should form when a self-gravitating system of total mass M gets compacted inside a region of circumference C, satisfying the condition:

$$C \le 2\pi R_s \tag{4.3}$$

R_s being the Schwarzschild radius for the system:

$$R_s = \frac{2GM}{c^2} \tag{4.4}$$

Thus,

$$C \le \frac{4\pi G}{c^2} M \tag{4.5}$$

This is clearly based entirely on the classical general relativity. However, since we are applying it to the collision of hadrons, quantum mechanical arguments must necessarily enter the picture. This is done by taking $R = R_0$ as the largest value of the hoop radius, the rest-frame radius, R_0 being the Compton wavelength, and make equal the fundamental length scales from the two pillars of modern physics.

Further, if m_0 is the rest-mass of each colliding particle (taken to be equal for simplicity), we have the total mass trapped inside the Schwarzschild radius as $M = 2\gamma m_0$, γm_0 being the Lorentz transformed mass of each particle, and γ is the Lorentz boost factor,

$$\gamma = \sqrt{1 - \frac{v^2}{c^2}} \tag{4.6}$$

Using the basic hoop conjecture, we obtain, the condition for formation of a black hole through the relation:

$$\gamma \geq \frac{Rc^4}{4G_h m_0} \tag{4.7}$$

Here m_0 represents the rest mass of each nucleus, so that for a system boosted to γ, the total mass of the system would be $M = 2\gamma m_0$. R can normally be taken to be the Compton radius $R = \hbar c/M$, to which the system collapses.

The above condition is very hard to satisfy if we assume G to be the regular Newtonian value given by $G_N = 6.67 \times 10^{-11}$ in standard S.I units. But in the context of our dual space-time approach to the strong interactions, we replace G_N by G_h, where G_h is the nuclear "chromo-gravity" value given by $G_h = 10^{38} G_N$.

With this new hadronic value of G_h, we expect the condition above to be easily satisfied, suggesting the formation of an abundance of black holes. These "new" black holes formed from the mergers will be larger hadrons, or "resonances", since we are modeling all hadrons as well as nuclei by "strong nuclear" black holes. These can ideally decay via thermal Hawking radiation to all kinds of particle-antiparticle pairs.

In terms of energy, the center-of -mass energy of the system must exceed the Plank energy for a black hole to form, and therefore for the emission of gravitational waves. Again, taking R to be the de Broglie wavelength given by the Compton wavelength $R = \frac{\hbar c}{M}$, we can derive the condition for black hole formation as when:

$$M \geq \sqrt{\frac{\hbar c^5}{G_h}} \tag{4.8}$$

where G_h is as before the large "nuclear" value that G takes on inside the strongly interacting particles. Here again we see that with the usual Newtonian gravitation, this criterion is very hard to satisfy, unless we change the Plank scale energy to a much lower value. This has been done so far exclusively by means of introducing large extra dimensions or "warped" dimensions. On the other hand, we get the same results by merely using a geometrical algorithm, which leads to a large value of G inside hadronic particles in a very natural manner.

4.4. Gravitational Dominance in High-Energy Collisions

For collisions where the center-of-mass collision energies $E_{CM} \gg M_p$, quantum gravity effects are known to be suppressed as powers of the ratio M_p/E_{CM}. This implies that ultra-relativistic collisions at very high center-of-mass energies can be treated like a classical process, rather than as a quantum process. A similar argument was put forth in 1983 by t'Hooft [42], who emphasized the dominance of gravitational force over all the other interactions in collisions at or above the Plank scale, justifying using the classical tools of GR. So, at ultra-relativistic energies, when graviton exchange dominates over all other processes, we are dealing theoretically with the highly non-linear regime of the strong gravitational fields. Therefore, black hole production becomes an inevitable consequence. See also [43] [44] [45].

The main issues of concern are the dynamics of black hole formation, and the inelasticity, ε, of the collision process, *i.e.* that fraction of the initial energy of the system, E, that is converted to gravitational energy and radiated away. There have traditionally been two approaches to study this problem. One is by analysis using Hawking's Area Law [41], and the second is by modeling each of the colliding particles as shock waves, and using an apparent horizon bound [46].

4.5. Inelasticity Bounds

4.5.1. Bounds Using Apparent Horizon and Trapped Surface

In this approach, relativistic heavy-ion collisions are modeled using two Aichelberg-Sexl [46] gravitational shock waves moving towards each other at the speed of light. In 1971, Aichelberg and Sexl applied a boost to the Schwarzschild metric. While keeping the lab frame energy, E_0, fixed, they allowed the boost parameter γ to become arbitrarily large, *i.e.* $\gamma \to \infty$. Since there is a dominance of kinetic energy, we can therefore assume that the very high energy collision of particles can be described by a semi-classical process, characterized by a relative boost parameter, $\gamma = \frac{1}{\sqrt{1-v^2}}$ in units where $c = 1$, and an impact parameter, b. At velocities $v \to c$, the severe relativistic length contraction would turn the initial state into two "planar shockwave" slices of curved space, the rest of the geometry being approximated by a flat space (see metric below). This means that although before the collision, curvatures can be made arbitrarily small, compared to other characteristic scales, the energy in the infinite boost limit must describe the geometry of a gravitational shock wave.

We use null co-ordinates u, v, along with X and Y, where the u and v are defined in terms of t and Z according to:

$$u = \frac{1}{\sqrt{2}}(t - Z) \quad \text{and} \tag{4.9}$$

$$v=\frac{1}{\sqrt{2}}(t+Z) \tag{4.10}$$

As we saw, δ-function singularities must appear in the expression for the curvature tensor of the metric. So, each of the colliding particles can be written as an Aichelberg-Sexl shock metric in the form:

$$\mathrm{d}s^2=2\mathrm{d}u\mathrm{d}v+4E_{cm}\ln\left(X^2+Y^2\right)\delta(u)\mathrm{d}u^2-\mathrm{d}X^2-\mathrm{d}Y^2, \tag{4.11}$$

E_{cm} is the energy in the lab frame.

The spacetime describing the collision process is then a union of the two AS shock waves. The fact that a closed trapped surface appears in the future of the collision must signal the production of a black hole (assuming, of course that cosmic censorship does actually still hold!).This approach gives us a value of 29% for the total CM energy to be radiated away as gravitational waves (This is the same result obtained in [47]).

4.5.2. Bounds Using Hawking's Area Theorem

We do an area calculation here in the in the context of GDA, and show for the first time that that we get the same inelasticity factor as that of Hawking [41] and Penrose [47].

According to the statement of Hawking's Area Theorem, during any process involving black holes, *the area of the event horizon can only increase or remain constant but can never decrease*.

Let us apply this to the two colliding Kerr-Neumann nuclei.

Let S_1 and S_2 be the surface areas of the two colliding nuclei and let S_f indicate the area of the final merged black hole. Then according to Hawking's Area Theorem, we should have the inequality:

$$S_f\geq S_1+S_2 \tag{4.12}$$

For a Kerr-Neumann black hole, with mass M, charge Q, and angular momentum, J, the surface area is no longer spherical, and we no longer have a fixed radius as such.

Using Boyer-Lindquist coordinates [48], we can write down an expression for the horizons, that occur at $r=r_{\pm}$, where $r_{\pm}$ can be written in terms of the total mass M, the angular momentum J, and the charge Q.

In order to solve for the horizons, the condition for a zero cosmological constant is [49]

$$r^2-2Mr+a^2+Q^2=0 \tag{4.13}$$

Therefore, as shown in Sec 4, in the special case of a zero cosmological constant, one obtains either 0 or 2 horizons, corresponding to the r values given by:

$$r_{\pm}=m\pm\sqrt{m^2-a^2-Q^2} \tag{4.14}$$

Regge-like conditions are obtained when $m^2=a^2+Q^2$, which is obtained as one of the stable solutions of the black hole, since it leads to temperature $T_n=0$, when $r_+=r_-=m$ [50].

In the special case of a zero cosmological constant, one obtains either 0 or 2 horizons, corresponding to the two radial values given by:

$$r_{\pm} = \frac{GM}{c^2} + \sqrt{\left(\frac{GM}{c^2}\right)^2 - \left(\frac{\sqrt{G}Q}{c^2}\right)^2 - \left(\frac{J}{Mc}\right)^2} \tag{4.15}$$

In geometrical units, we have:

$$r_{\pm} = m \pm \sqrt{m^2 - a^2 - Q^2}\text{ , where }\ a = J/Mc\text{ , }\ m = GM/c^2$$

The event horizon we want is the outer event horizon r_+.

The appropriate line element $\mathrm{d}s_+$ on the surface r_+ can be written as:

$$\begin{aligned} \mathrm{d}S_+^2 &= g_{\theta\theta}\mathrm{d}\theta^2 + g_{\phi\phi}\mathrm{d}\phi^2 \\ &= \left(r_+^2 + a^2\cos^2\theta\right)\mathrm{d}\theta^2 + \left(r_+^2 + a^2 + \frac{a^2\left(2Mr_+ - Q^2\right)\sin^2\theta}{r_+^2 + a^2\cos^2\theta}\right)\sin^2\theta\mathrm{d}\phi^2 \end{aligned} \tag{4.16}$$

$$\mathrm{d}S_+ = \left(g_{\theta\theta}\right)^{1/2}\left(g_{\varphi\varphi}\right)^{1/2}\mathrm{d}\theta\mathrm{d}\phi \tag{4.17}$$

The horizon area would be the surface integral of the above expression, carried out over appropriate limits for θ and ϕ:

$$S_+ = \int_0^{\pi}\mathrm{d}\theta\int_0^{2\pi}\left(g_{\theta\theta}\right)^{1/2}\left(g_{\varphi\varphi}\right)^{1/2}\mathrm{d}\phi \tag{4.18}$$

After integration and simplification, we finally get the expression for the surface of the horizon as:

$$S_+ = 4\pi\left[r_+^2 + \left(\frac{J}{Mc}\right)^2\right] \tag{4.19}$$

$$S_+ = 4\pi\left(2M^2 - Q^2 + 2M\left(M^2 - a^2 - Q^2\right)^{1/2}\right) \tag{4.20}$$

Dropping the + sign for simplicity, let S_1, S_2 and S_F denote respectively the surface areas of the two colliding ions, and the final merged black hole, M_1, M_2 and M_F to represent the corresponding mass terms, etc., we have:

$$S_f = 4\pi\left(2M_f^2 - Q_f^2 + 2M_f\left(M_f^2 - a_f^2 - Q_f^2\right)^{1/2}\right) \tag{4.21}$$

Now, we will use the area theorem 4.11, to determine the inelasticity of the collision and the maximum percentage radiated away as gravitational waves:

Assuming that the initial colliding objects have identical masses, charges and spins, denoted by M, J and Q, (for example, they could be two identical protons colliding with each other), and let us assume that the final charge of the merger is still $Q_f = Q$, though the resulting spin is different, given by a_f.

$$\begin{aligned} &2M_f^2 - 2Q^2 + 2M_f\left(M_f^2 - a_f^2 - Q^2\right)^{1/2} \\ &\geq 2M_1^2 - Q^2 + 2M_1\left(M_1^2 - a^2 - Q^2\right)^{1/2} + 2M_2^2 - Q^2 + 2M_2\left(M_2^2 - a^2 - Q^2\right)^{1/2} \end{aligned} \tag{4.22}$$

Now, imposing the condition, $m^2 = a^2 + Q^2$, in all the cases, which leads to the desired Regge-like behaviour, we get:

$$2M_f^2 - 2Q^2 \geq 4M^2 - 2Q^2 \text{, implying:} \tag{4.23}$$

$$M_f \geq \sqrt{2}M \tag{4.24}$$

We thus have the lower bound for the resultant black hole as $\sqrt{2}$ times the initial mass of each black hole, or at least as massive as 71% of the total combined mass (2*M*).

This should give us the upper bound for total radiation emitted as gravitational energy to be the remaining, which can be extracted as:

$$E_{gw} \leq 2M - \left(M_f\right)_{\min} \leq 2M - \sqrt{2}M \leq \left(2 - \sqrt{2}\right)M \tag{4.25}$$

This is the same result obtained by Penrose [43]. It is interesting to note that our geometrical dual approach, *leads to the same upper bound*, which is that a maximum of 29% of the total initial mass can be radiated away as gravitational waves. Incidentally, other methods [51] [52], and even those using Bondi News function [53] have also yielded similar results (*i.e.* an inelasticity of 29%). This further supports the idea that GDA matches all earlier results and could well provide an alternate route to the dynamics of ultra-relativistic heavy-ion collisions.

Another important feature of our unique approach is the following: the use of "color black holes" for colliding ions would imply that the final results of the "ultra-relativistic" collision will be totally insensitive to the details of the structure of the colliding objects, *i.e.* matter does not matter'. Therefore, the GDA does allow for a universal analysis, implying that the exact quark structure is no longer so relevant! This is an important example of the kind of universality one looks for in physics.

We end this section by noting that in the context of AdS/CFT, see for example, in [54], arguments indicate that the dynamics of shock wave collisions does not have a suitable description within AdS/CFT. Thus, since the formation and existence of a trapped surface must necessarily indicate that a black hole has formed, the GDA approach is more viable in this context also, versus the AdS/CFT.

4.6. Preliminary Analysis

In this manuscript, a brand new, unorthodox scenario for lowering the Plank energy in $D = 4$ is proposed, without the need for any extra or any curled-up dimensions. This is done in the context of the proposed dual curved spacetime geometrical description of the strong interactions, where the strong force takes on the characteristics of an effective "strong gravity" in the IR section, and the spacetime inside hadrons is approximated by a Kerr-Newman de Sitter black hole type of metric.

The main finding of our work is this: In the collision of high-speed nuclei, modeled as "strong color black holes", high frequency gravitational waves (perhaps of the QCD induced strong gravitational or chromo-gravity type), should be produced in moderate to copious amounts, and moreover, these should be capable of detection with existing/modified LIGO equipment.

Further, we are claiming that the total energy lost to gravitational radiation is significantly higher in our new paradigm, and in fact dominates the missing energy.

Our GDA formalism also predicts that black holes will be produced at colliders in high numbers. However, these black holes are vastly different from the ones that are predicted in ADD/RS scenarios. Owing to the very high energy gravitational waves, the black hole that are produced in the geometrical algorithm will be much smaller than the ADD black holes, and will be in the GeV range In fact, these black holes will just be regular hadrons, and hadronic resonances, arising from the merger of the colliding protons and nucleons.

Being just regular Standard Model particles, our GDA black holes will therefore not display the tell-tale phenomenological radiation signatures of the extra-dimensional black holes.

We would like to emphasize here that the focus at detectors should not be on a search for specific signatures of black hole production, but rather a search for signatures of the high frequency gravitational waves (HFGW) that we predict will be produced.

5. Phenomenology

In modelling the ultra-relativistic collision of heavy ions, we have assumed a gravity dominance, and have ignored all other forces. This strategy is completely justified, and has been supported by several authors, especially in the context of ultra-relativistic high-energy collisions. It is even more true in the classical setting we are assuming, where gravity is the only force that gets stronger at increasing energies.

5.1. Gravitational Waves and Black Holes as GDA Main Observables

The semi-classical black holes that characterize the ADD mergers are supposed to be very hot, typically hundreds of GeV, and therefore decay extremely fast, in the extremely short lifespan of $t \sim 10^{-27}$ sec, using arguments from classical GR black holes. So, in the case of ADD black holes, one would expect spectacular displays, including high multiplicity, highly democratic and spherical decays, such that the final state particles carrying away hundreds of GeV of energy. Such dramatic events should have shown up but, in reality, have never been observed in any of the LHC runs.

In contrast, In the GDA scenario, we do not expect any spectacular decay signatures. The color black hole mergers formed immediately after the collision will be unstable, and we expect them to decay also in multi-phase stages, like the ADD black holes, but they will eventually decay to regular hadrons of the Standard Model.

The usual four-stage process is expected for the GDA black holes as well, namely 1) appearance of a CTS (closed trapped surface) from the merger of the two AS shock waves; 2) the balding phase, where the newly formed asymmetrical merged black hole is expected to emit the HFGW by emitting characteristic ringing Quasi-Normal modes (QNM's), before finally settling down into a cylindrically symmetric Kerr rotating hole. So, after this phase, the merged black hole would just settle into a regular hadronic black hole, rather than the Myers-Perry multi-dimensional black hole of ADD scenarios; 3) A spin-down phase, the black hole might lose angular momentum through the emission of Hawking radiation; 4) The mass and/or the Hawking temperature approaches the Plank scale, which is now much lower. Information loss problem is avoided in the GDA scenario, since the black holes will not decay completely, or leave a remnant, but reach the Plank mass, and become stable.

As shown in Section 4, our predicted black holes will be in a much a smaller energy range, *i.e.*, ~ a few GeV, as well as have the masses in the proton range, rather than 5000 times the mass of the proton. Also, they will have the dimensions of a fm (Fermi), the size of a proton, rather than being 1/1000th of a fm. We expect a large number of these new black holes to form at the GeV range, by the mergers of the original colliding KNdS black holes. As a consequence, a significant amount of energy is predicted to be lost to the very energetic high frequency gravitational waves. Further, all emissions including any SM particles, as well as gravitational radiation are emitted into our regular four dimensions of space-time, there being no distinction between "brane" and "bulk" in the GDA scenario [55]. Hence the *only real observable signature* is predicted to be the high to ultra-high frequency gravitational waves emitted during the merging phase.

5.2. Why Current LHC Searches Have Failed

1) Current gray body factors from the Monte Carlo event generators for both the inelasticity as well as the energy and size range of the black holes produced are based on the ADD/extra/warped dimensional scenarios, and therefore are inaccurate, leading to the prediction of the incorrect range of black holes, and thereby the inability to detect them.

2) Our GDA black holes will be in the GeV range, and therefore likely to be just regular hadrons, and hadronic resonances.

3) Current searches are for gravitational waves are in the wrong frequency range, hence the inability to observe them. Most of the collision energy is radiated away as high to ultra-high frequency gravitational waves.

5.3. New Search Criteria: Detection of Gravitational Waves

In our scenario, all hadronic particles (including the colliding nuclei at RHIC), are modeled as Kerr Newman de Sitter black holes. In an ultra-relativistic collision of such black holes, where a strong nuclear-strength gravity is the dominant force, classical relativity tells us that gravitational waves appropriate to the "hadronic" black holes undergoing collisions should be produced.

We also predict that at impact parameters smaller than the Schwarzschild radius for the relevant parameters, the cross-section would be dominated by an inelastic process, in which the collision produces a bigger black hole. For large and intermediate impact parameters, there would be various two-body scattering amplitudes, and the scattering would be harder to predict.

In our GDA scenario, both the merger and ring-down phases are expected to produce copious amounts of high frequency gravitational waves. The GW signal would give us significant information about the structure of the black holes that were merged, also shedding light on whether spacetime is curved inside their regions. Therefore, such detection and testing is crucial.

It is anticipated that future upgrades to advanced LIGO may be needed to detect subtle measurements such as those required for QNM's from mergers of Kerr-Newman de-Sitter black holes. We expect GR to pass the test in this strong gravity sector also.

Special signatures for the gravitational waves would be present because of the formation of the quark-gluon plasma, or for other situations such as if cosmic censorship is violated, etc.

5.4. Luminosity, Amplitude and Frequency of Proposed Gravitational Waves

With the same approximation we used for the colliding black holes, we now use rough order of magnitude calculations to obtain expressions for the luminosity of the gravitational waves, the amplitude as well as the frequency, so as to better estimate the feasibility of detection. More detailed calculations will be left for a future manuscript. Here we attempt to show that these gravitational waves would indeed be of very high frequency.

Using for simplicity the linearized Einstein equations with source term, we start with the usual solution giving the wave amplitude:

$$h^{\rho\sigma} = -\frac{\kappa}{4\pi}\int \frac{T^{\rho\sigma}\left(t-\left|\boldsymbol{x}-\boldsymbol{x}'\right|,\boldsymbol{x}'\right)}{\left[\boldsymbol{x}-\boldsymbol{x}'\right]}\mathrm{d}^3x' \tag{5.1}$$

The quadrupole moment of the source can be written as:

$$Q_{\rho\sigma}^{TT} = \int \rho\left(x^{\rho}x^{\sigma} - \frac{1}{3}\delta^{\rho\sigma}r^2\right)\mathrm{d}^3x\,. \tag{5.2}$$

The wave amplitude is therefore seen to be proportional to the second time derivative of the source, and can be written as:

$$h^{\rho\sigma} = \frac{2G}{c^4 r}\ddot{Q}_{TT}^{\rho\sigma}\left(t-r/c\right), \tag{5.3}$$

In the above, ρ represents the average matter density, $Q_{TT}^{\rho\sigma}\left(t-r/c\right)$ is the quadrupole moment in the transverse-traceless gauge, measured at the retarded time $t_r = t-\frac{r}{c}$.

Although the above results were derived for the black hole binary, they are valid for all sources, as long as the wavelength is longer that the size R of the source.

We now write down expressions for the quadrupole gravitational power, or the luminosity in the gravitational waves. In general, gravitational power radiated is given in terms of the third-order time derivative of the quadrupole moment tensor, *i.e.*

$$L_{gw} = \frac{G_h}{5c^5}\left[\frac{\partial^3 Q_{ab}}{\partial t^3}\right]^2 \tag{5.4}$$

In the above, we are using the strong hadronic gravitational coupling constant G_h in place of the regular Newtonian gravitational constant, G_N.

The quadrupole moment of a system can be roughly estimated as the product of the total mass M of the part that moves, and the square of the average size, R, of the system.

Then the quadrupole triple derivative is given by:

$$\frac{\partial^3 Q_{ab}}{\partial t^3} \sim \frac{MR^2}{T^3} \sim M\frac{v^2}{T}, \tag{5.5}$$

where v is the velocity of the moving part, so that the right hand side is just the kinetic energy of the non-spherical moving part.

Take $v = R/T$ as the average velocity of the moving mass M. and $T = \sqrt{\frac{R^3}{G_h M}}$ for this self-gravitating system, we can now get a rough estimate of the gravitational wave luminosity, which can then be written as:

$$L_{gw} = \frac{G_h}{5c^5}\left[\frac{Mv^2}{T}\right]^2 \tag{5.6}$$

$$L_{gw} = \frac{G_h^4}{5c^5}\frac{M^5}{R^5} = \frac{G_h^4}{5c^5}\left(\frac{M}{R}\right)^2 v^6 \tag{5.7}$$

Writing down the Schwarzschild radius of our source as $R_s = \frac{2G_h M}{c^2}$, we can finally write down for the luminosity:

$$L_{gw} = \frac{c^5}{G}\left(\frac{v}{c}\right)^6\left(\frac{R_s}{R}\right)^2 \tag{5.8}$$

The maximum luminosity can be found by if the size of the system is the Schwarzschild radius, and v becomes equal to the velocity of light, which matches our conditions of ultra-relativistic collisions of elementary particle sized strong black holes!

So, maximum power is generated for these waves. At these ultra-relativistic velocities, we can write

$$T = \frac{R_s}{c} \tag{5.9}$$

This gives us the frequency, ν of the gravitational wave quanta, as well as the energy per high frequency graviton as:

$$\nu = \frac{1}{T} \text{ and } E_q = \hbar \nu \tag{5.10}$$

The total mass M of the colliding nuclei can be estimated to be ~14 TeV/c^2, giving a total energy involved in the collision to be ~14 TeV.

The corresponding Schwarzschild radius is:

$$R_s = \frac{2G_h M}{c^2} \sim 10^{-15} \text{ m} \tag{5.11}$$

This gives the time scale of the collision as

$$t \sim 10^{-23} \text{ sec} \tag{5.12}$$

We next write compute the total energy released in the form of gravitational waves, which is given by:

$$E = \frac{G_h}{c^5} \left[\frac{M v^2}{t} \right]^2 t \tag{5.13}$$

For two typical colliding nuclei, the total energy of the "Little Bang" is Mc^2, where M is the total mass involved (combined mass of the two nuclei).

Using equations above for ν and E_q, this finally allows us to get the energy of each high frequency gravitational quanta as E_q ~ 70 - 100 MeV, and the frequency of the gravitational wave expected to be emitted turns out to be in a much higher range than seen before with a frequency of

$$\nu = 10^{23} \text{ Hz !} \tag{5.14}$$

Finally, the estimate of amplitude: Using the same order of magnitude calculations:

$$h^{\mu\nu} = \frac{2G_h}{rc^r} \ddot{Q}_{TT}^{\mu\nu} (t - r/c) \tag{5.15}$$

$$h^{\mu\nu} = \frac{2G_h}{rc^r} K \sim \frac{G_h}{c^4} \varepsilon E_T \text{ ,} \tag{5.16}$$

where K is the kinetic energy contribution from the relevant motion that can generate the gravitational waves, and ε is the efficiency of this conversion.

Thus, relevant mathematical analysis from (5.16), along with the enormous value of G_h leads to the inevitable conclusion that the gravitational luminosity, as well as the amplitude can indeed both be sizable, indicating that we do have the capability to detect these high frequency waves!!

So, although such HFGW's have not theoretically shown so far to be relevant to our universe, our calculations reveal that they should be an outcome of heavy ion collisions at RHIC and other accelerator sites, and further, should be produced in copious amounts, and detectable by future planned LIGO!

6. Main Results and Discussion

Interestingly, we have shown that no matter the approach used for the description of hadrons using geometrical algorithms, a strong "pseudo" or "chromo-gravity" is an inevitable consequence. This is not the usual weak gravity of

Newton, but a gravity in the strong regime, from which quark confinement arises in a completely natural manner.

This "strong" field inside the hadron has been completely identified by several authors and several different methods with a "strong" gravitational field which has a strength of 10^{38} times the gravitational force that we experience on Earth. Therefore, in ultra-relativistic high-energy collisions, this strong gravity would dominate, producing "strong" QCD-induced gravitational waves, and in copious amounts, in both the "merger" and "ring-down" phases.

Our main results from this radical new approach are summarized below:

1) "*Naturalness*" has been restored and the hierarchy problem has been solved by introducing gravity into the Standard Model, in the form of a "strong gravity/gauge" coupling that is relevant in the IR segment of QCD. This prevents the need for unreasonable "fine-tuning", where one has to add huge quantum corrections to the Higgs mass just to push the electroweak scale up to the Planck scale.

2) *Jet-quenching*: The near total suppression of hard scattering events (known as jet quenching) has a ready explanation in the GDA paradigm. In perturbative QCD (due to asymptotic freedom), there are typically a multitude of hard scattering events, with large transverse momentum. However, collider data shows a significant attenuation or absorption of such hard scattering events (jet-quenching) over the tiny length scales of the QGP, suggesting the presence of a very strong coupling. This phenomenon has currently no satisfactory explanation within the framework of perturbative QCD, except to introduce the problematic Color glass Condensate (CGC). On the other hand, in our approach, the CGC is replaced by the merged black hole resulting from the two colliding color KNdS black holes, and this process is indeed dominated by the strong coupling force of gravity. In such a non-perturbative regime, we can expect significant jet quenching, and further, it is easy to establish a one-to-one correspondence between properties of the black hole, and that of the resulting perfect fluid.

3) The GDA provides a natural explanation for the very difficult problem of color confinement [6] [11] [12].

4) Rising Regge trajectories of baryons and mesons are also predicted as observed at detectors! [9] [11].

5) We have explained why the current search criteria at LHC has failed, and what to search for instead.

6) Our most exciting result is our mathematical analysis revealing that HFGW's must emerge as a testable outcome of the presence of gravity in hadronic matter.

We present a **Table 1** to display our main results.

7. Concluding Remarks

It has been shown that a geometrical version of the gauge/gravity correspondence promises to be a new and effective tool for exploring the IR segment of

Table 1. Summary of main results.

Unresolved Issue	Current Status in String based scenarios	Status using our proposed GR based geometrical dual approach.
Hierarchy Problem	Extra dimensional and AdS/CFT methods have been unable to resolve the issue, and the predictions they make are not supported by collider data.	The GUT scale is significantly lowered without the need for SUSY-based scenarios, and without the need for extra/warped dimensions.
Integrating gravity into the standard model	SUSY-based models as well as methods based on gauge-gravity connections like AdS/CFT have generally been proven to be ineffective, so far.	In our GR-based dual gravity approach, gravity in the strong sector automatically emerges in non-perturbative QCD.
Quark confinement	Cannot be currently explained using conventional quantum field-theoretic and/or string-based methods.	Readily emerges as a natural consequence of the geometrical algorithm used and arises from color confinement.
Jet Quenching	Has no satisfactory explanation within any of the current models	Explanation described in Sec 5 of manuscript

QCD. Unlike lattice QCD, the need to assume an unreasonably large number of colors does not arise, and unlike the AdS/CFT based gauge/gravity theories. there is no need for supersymmetry or extra dimensional spaces.

Using the conjectured equivalence between gravitational confinement and color confinement, in the context of KNdS black holes, it has been successfully shown why the current parameters for LHC searches are wrong, and more importantly, what the new search criteria should entail.

Perhaps more importantly, it has been shown for the first time that if a strong gravity, or "effective" gravity is in fact operative in the nuclear domain, and if General Relativity continues to be valid in this regime, the tell-tale signatures of such a force should be manifest in the phenomenology at LHC and RHIC, in the form of high to ultra-high frequency gravitational waves, and not in the form being currently sought after. The proposed waves should be capable of detection by current or planned LIGO detectors.

If found, these waves could open up an unprecedented window into several new and unchartered territories and launch the brand-new field of high frequency gravitational wave physics. This would, without a doubt, carry the seeds for incredible engineering applications.

Conflicts of Interest

The author declares that no known competing financial interests or personal relationships could have influenced any aspect of the work reported in this paper.

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