Developments in Classical and Quantum Inertia
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Abstract: The equivalence principle suggests a common cause of gravitational and inertial mass. Many notable physicists of the last century attempted to derive inertia from gravity, but no consensus formed. We summarize the old controversies and developments which shed fresh light on them, as well as a newly available quantum formulation in which inertia is the primary effect, and relativistic gravity is a consequence.

Key words: inertia, gravity, quantum, measurement, relativity, uncertainty, equivalence, Mach’s principle

I. Introduction
As far back as the 6th century, it was observed that different masses fell at the same rate. This experiment was sufficiently intriguing that it was repeated with successively higher precision by Galileo, Newton, Eotvos, Dicke and others until confirmed to better than one part in 10^13, and with respect to the Earth, Sun and galactic center [1]. Direct proportionality of the gravitational attractiveness property of matter (gravitational mass) and the acceleration resistive property of matter (inertia) are thus confirmed to that degree, and often codified as the equivalence principle (EP). These circumstances strongly imply that the two are one and the same.

It seems that if one had a theory of inertia, one would also have a theory of gravity. Einstein followed that line of thinking and chose the ideas of Ernst Mach (foreshadowed in the writings of George Berkeley) for his theory of inertia. Mach thought that motion, acceleration and mass could be defined only relative to other masses in the universe, in flat contradiction to Newton’s theory of absolute space [2].

Einstein coined the phrase Mach’s Principle (MP), and from this and the EP developed his theory of gravity, i.e. General Relativity (GR) [3]. GR is one of the most successful scientific theories of our time. But Einstein shortly began to contend with two disappointing problems: controversy over whether the new theory truly embodied Mach’s principle, and difficulty unifying the theory with other forces of nature, then electromagnetism, but later the Standard Model (SM) of particle physics and the newly emerged theory of quantum mechanics (QM).

II. GR and QM
It is well known that the Standard Model does not address gravity. Naturally there is speculation about gravitons but true quantum models of gravity generally contain esoteric concepts such as higher dimensional spaces well beyond the SM. Einstein contributed greatly to the development of quantum mechanics, but came to differ with the prevailing interpretation and felt that the more nondeterministic interpretations would undermine his theory of gravity, perhaps most forcefully arguing this position in a paper describing the Einstein-Podolsky-Rosen paradox [4]. In this thought experiment, it is shown that QM predicts a linkage between the quantum states of certain remote particles, and when one is measured the other produces a correlated measurement which cannot be explained by pre-arranged correlation, regardless of the distance of separation. The development of the Bell Theorem gave physicists a way to test this prediction, and several decades of testing, while not eliminating all loopholes, are suggestive that the effect exists in nature [5].

A key feature of the Standard Model is the mechanism by which several particles in the model obtain their non-zero rest masses through interaction with the Higgs field, which presumably when quantized yields the Higgs boson [6]. Confirmation of this mass-conveying particle is the subject of a high profile long term search, and a subject of articles in the popular media.

The Higgs boson is also the subject of some confusion. For example, an internet search for the term “Higgs gravity” yields countless blog entries and a few websites

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asking about or claiming a connection between the Higgs boson and gravity, but no scholarly articles. As readers of this journal are thoroughly aware, the Higgs field is an energy field and energy is a gravity-producing term in the Einstein field equation of GR. This mechanism already has mass, and conveys it to the other particles. It doesn’t generate or create mass.

So the SM really is silent upon the origin of inertia, and attempts at quantum gravity do not develop a theory of inertia and then gravity, but proceed directly to gravity. In fact, all quantum fields thus far have been based on the energy-time version of the uncertainty principle, and are energy fields. Since inertia is energy, such fields are not ideally suited to explaining inertia, and the attempt leads to various circularities and singularities. Other conundrums in quantum gravity include questions such as “Why is gravity so weak compared to other forces?” And there is the issue of background independence. We will reconsider these problems at the end of our discussion.

III. GR and Mach’s Principle

Maxwell was disturbed by the always negative potential energy when he attempted to apply his field equations to gravity, but Heaviside, Lorentz and Poincare all made published attempts around the end of the 19th and beginning of the 20th centuries, which are similar to the weak field linearized version of GR used today [7]. But it was Einstein in 1912, in the midst of developing GR, who posed the question in a paper title: “Is there a gravitational effect which is analogous to electrodynamic induction?” [8] However, Einstein does not use the electromagnetic formulation to argue his point. Rather, he uses gravitational potential energy, noting the relation of any kind of energy to inertial mass from the theory of Special Relativity, and after some analysis concludes the incremental contribution of inertia \( \Delta m \) from a spherical shell of mass \( M \) and radius \( R \) to a point mass \( m \) at its center is

\[
\Delta m(M, R) = GMm / Rc^2 \tag{1}
\]

(restatement of equation 2 from the 1912 paper). There is no actual argument involving "electrodynamic induction." Einstein only suggests that this effect he has separately derived is analogous. He goes on to say “This suggests that the entire inertia of a mass point is an effect of the presence of all other masses,” and in a footnote observes “This is exactly the same point of view that E. Mach advanced.”

In his book The Meaning of Relativity, Einstein uses the field equations of GR to the same ends, establishing and defending a claim that GR validates Mach’s principle [9]. Einstein notes three features to be expected of a Machian theory:

1. “The inertia of a body must increase when ponderable masses are piled up in its neighbourhood.”
2. “A body must experience an accelerating force when neighbouring masses are accelerated, and, in fact, the force must be in the same direction as that acceleration.”
3. “A rotating hollow body must generate inside of itself a ‘Coriolis field’, which deflects moving bodies in the sense of the rotation, and a radial centrifugal field as well.”

He then goes on to point out small differences between GR and the three electromagnetic based gravity theories mentioned earlier.

Almost immediately arguments began over the emphasis on Mach’s principle. Mach himself had established this tone, taking a historical approach to mechanics and commenting critically upon the approach and ideas of numerous revered intellects. Mach’s arguments inspire Einstein’s three points, but do not contain them explicitly. Mach’s most precise statement about inertia is the following:

“Instead of saying, the direction and velocity of a mass \( \mu \) in space remain constant, we may also employ the expression, the mean acceleration of the mass \( \mu \) with respect to the masses \( m, m', m'' \ldots \) at the distances \( r, r', r'' \ldots \) is = 0, or

\[
d^2 \left( \sum mr / \sum m \right) / dt^2 = 0 \tag{2}
\]


On inspection we easily find that (1) and (2) are compatible. But as to whether such simple formulations can be found in GR, the view of critics to come for the next century is already summed up in de Sitter’s 1917 comments:
“In Einstein’s theory of general relativity there is no essential difference between gravitation and inertia. The combined effect of the two is described by the fundamental tensor $g_{\mu\nu}$ and how much of it is to be called inertia and how much gravitation is entirely arbitrary. . . . Part of the $g_{\mu\nu}$ can be directly traced to the effect of known material bodies, and the common usage is to call this part ‘gravitation,’ and the rest ‘inertia.’ The extrapolation which most naturally offers itself, and which is also tacitly made in Newton’s theory of inertia, is that the $g_{\mu\nu}$ retain the [local values] at all times and distances up to infinity. It has been pointed out . . . that in this theory inertia is not relative. The values [of $g_{\mu\nu}$] are not invariant: The boundary-values of the $g_{\mu\nu}$ at infinity are different in different systems of co-ordinates. Einstein and others have therefore tried to find another extrapolation, by which the $g_{\mu\nu}$, while in our neighbourhood retaining the [local values] with the approximation demanded by the observations, would at infinity degenerate to a set of values which would be the same for all systems of reference.

Only the deviations of the actual $g_{\mu\nu}$ from these values at infinity are thus due to the effect of matter, through the mechanism of the equations [of GR]. If at infinity all $g_{\mu\nu}$ were zero, then we could truly say that the whole of inertia, as well as gravitation, is thus produced. This is the reasoning which has led to the postulate that at infinity all $g_{\mu\nu}$ shall be zero. I have called this the mathematical postulate of relativity of inertia.

If all matter were destroyed, with the exception of one material particle, then would this particle have inertia or not? The school of Mach requires the answer No. If, however, by “all matter” is meant all matter known to us, stars, nebulae, clusters, etc., then the observations very decidedly give the answer Yes.” [10]

But exciting new developments would soon diminish the relevance of old concerns.

**IV. Astronomical Observations and Tests**

When Einstein formulated GR, the observed (known) universe was limited approximately to the Milky Way. The nebulae were noted, but it was not known what they were and they were supposed by many to be within the Milky Way. By the 1930s, the Hubble expansion was found and Einstein rehabilitated his $\lambda$ constant. Originally added both to produce a static universe and to rule out some of the non-Machian solutions, he now used it to produce the dynamic expansion.

By the time a young Dennis Sciama was writing his dissertation, published in 1953, regular increases in size of the observed universe were so taken for granted that he could turn de Sitter’s argument around, and say that inertia theory predicts that vastly more matter in the universe will be found [11]. At the end of the century, Ghosh reported that sufficient matter had been found [12].

A second novel feature of Sciama’s inertia was his proposal that its sources were limited to the visible horizon. He also explains retardation effects in the usual way, i.e. sources can be treated as being exactly where they are seen to be at the moment of observation. By
this visibility mechanism, the boundary conditions are pushed into irrelevance, because they are not visible and can have no effect.

Sciama did not use the energy argument of Einstein's 1912 approach, or the equations of GR. Instead, he used the gravitational analogy to electromagnetism and an induction concept in which inertia is due to “the radiation field of the universe.” However, he arrives at a similar conclusion in which inertia is proportional to a 1/R relationship. Sciama promised a follow on paper to place the theory fully in a GR context. But his colleague Davidson produced a paper saying the idea was already fully contained in GR [13].

Sciama’s vector formulation opened up another controversy. In 1958 Cocconi and Salpeter asked if inertia might have a dependency on the vector angle between the acceleration and the source masses [14]. For objects in an isotropic universe of course it would go unnoticed. But the nearness of a planet, star or galaxy might produce an anisotropic inertia. Soon two reports of tests appeared, led by Hughes [15] and Drever [16] using lithium-7, whose nuclear wave functions have different spatial distributions with respect to a magnetic field. No anisotropy was found.

Interpretations varied widely, with Brans and Dicke saying it was expected and confirming of Mach’s principle, and Weber disagreeing [17], with the latter’s views being taken up by Weinberg and stated as fact in a textbook [18].

Writing 20 years later, near the end of the century, Ciufolini and Wheeler [19] go back to the basic potential energy argument of 1912, full circle, but present it as only approximately true, since the modern complex view of space and time obscures the simple distance based formula of the earlier era.

V. Laws of Inertia

In the 21st century, actually beginning in 1999 with Jammer [20], a slew of authors began to sift through the pieces of the century-long debate that had produced so little consensus, and a series of monographs and compilations appeared: Ghosh in 2000 on an extended Mach’s principle [21], Sachs (ed.) in 2003 on Mach’s principle and the origin of inertia [22], and Petkov in 2012 on historical and modern concepts of inertia and gravity [23]. My apologies to any author I might have missed in this crowded thicket!

Almost every author or editor takes a particular viewpoint, however, and none represent the diversity of opinion that even this short paper has compiled, which was of course one of the reasons for this paper. Some gems have slipped through the selective sorting process. For example, the acceleration transform of G. Ascoli was never published by Ascoli, but is mentioned and derived in a textbook by Sard [24] and attributed to Ascoli.

There is a collection of such transforms in a recent paper [25], used to convert the measurements of one reference frame so they can be compared with the measurements of an observer in another reference frame. The transforms can be applied between two frames at different gravitational potentials, for example. We know well how to transform time, as it has had much attention. But the transformation of time implies differences in speed, in the case of mechanical clocks, and also differences in acceleration, and so on. There is a transform for force which is found nowhere else. It is derived based on conservation of momentum. For example, if an object seems to have twice the mass, it will be moving at half the speed, and a force is modeled as a series of momentum impulses.

These transforms apply whenever Lorentz length contraction and time skew (not time dilation, but the desynchronization of clocks associated with length contraction in relatively moving frames) are not needed. For example, between two different gravitational potentials, or between relatively moving frames where the measurements of interest have only components transverse to the relative motion and are therefore not subject to contraction and skew.

The question of isotropy vs. anisotropy is addressed by analyzing a free falling clock from an accelerating elevator. The mass of the clock mechanism (say for example a ball bouncing between two plates) appears greater to an observer, and the ball moves more slowly, no matter what the orientation of the clock. By equivalence, the same analysis applies to gravity. This
method uses an energy analysis to obtain isotropic inertia, similar to Einstein's 1912 and Ciufolini and Wheeler's 1995 approaches. And with all the testing of clocks in gravitational fields, including the ones sensitive to orientation mentioned earlier, the isotropy of inertia regardless of the configuration of source masses is well supported.

This point is worth a look in a different context, because it is the empirical basis for the most important law of inertia after Newton's three, alluded to above. Time transforms oppositely to inertia. Viewed in the context of GR, that means inertia transforms with the time coordinate. Of course we know that the proper inertia of a mass is constant in GR. The transforms are with respect to some observer frame, not the proper frame of the object. And the transforms are exactly what is required so that in the proper frame of the object, its mass is constant. If a clock ticks slower in a gravitational field, relative to a higher potential observer, and a mass is heavier and moves more slowly, then the slow ticking clock will show that the slow velocity (and therefore higher mass by inference) is normal, as the same distance per tick is covered as in a higher reference frame. In fact, Mach points this out specifically even before GR or the transforms were known. He goes on and on about measuring the motion of one thing simply by the motion of another (a clock), and finally declares: "It is utterly beyond our power to measure the changes of things by time. Quite the contrary, time is an abstraction, at which we arrive by means of the changes of things; made because we are not restricted to any one definite measure, all being interconnected. ... A motion is termed uniform in which equal increments of space described correspond to equal increments of space described by some motion with which we form a comparison, as the rotation of the earth." [2] p. 224

Take the example of a clock in a gravitational field to its ultimate conclusion. Place an object vanishingly near the event horizon of a black hole. The object cannot be extracted. Nor can it be moved laterally. Relative to a higher observer, it is stuck and moves very slowly in any direction, thus isotropy. Such a resistance to motion cannot be called anything but inertia. Yet, the combined system of the black hole and the in-fallen object has no more mass than the sum of the two components, and can be dragged around in space by suitable means (such as the gravity of nearby stars). The in-fallen object is only "massive" in regard to its position relative to the black hole, not the universe at large. So inertia is not even a unitary property of an object – we must specify inertia with respect to what other object or objects. The reader will immediately notice that this is another way of describing frame dragging. If we move either the black hole or the in-fallen object, the other gets dragged with it to a degree proportional to the mutual gravitational potential between them.

We now have brought the reader up to date with the currently available classical, relativistic picture of the characteristics of inertia, its behavior and sources:

1. Inertial and gravitational mass are empirically linked by equivalence, and a theory of either should lead to the other.
2. Observable particles may be empirically linked (as by entanglement) over great distances outside the domain of relativistic causality, and indeed, some take the view that there are no particles, only fields [26].
3. A formulation of inertia as approximately proportional to gravitational potential is at least empirically consistent with the observable mass in the universe.$^1$
4. Recognition that cross-frame measurement of inertia is linked to time dilation provides access to ample empirical evidence that local deviations in gravitational potential produce the expected changes in inertia predicted by point 3, though no change in inertia is ever locally noticed because of the same linkage to time dilation of the clocks used for measurement.
5. Inertia is empirically isotropic, and from an energy or equivalence analysis standpoint theoretically isotropic. We might tentatively

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$^1$ Papers are beginning to appear regarding possible gravitational effects from beyond the visible horizon, which might imply inertial effects, but this area of inquiry is too immature to comment on in this context, and does not yet challenge the approximate proportionality of inertia to mass-energy within the visible horizon.
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We presume that this argues against a pure electromagnetically analogy in which inertia is a derivative of back-reaction to motion (induction) in a vector force field. The induction method also might likely have difficulty explaining the trajectory of light rays.

6. We do not seem to be able to give a unitary description of the inertia of a single object based on a single scalar or vector quantity at a point in a field, because of frame dragging. If there are independent accelerations of nearby objects, these must be independently accounted. (However, the problem is minimized in practice because Newton’s law of action-reaction requires centers of mass of interacting systems to remain un-accelerated, and a cleverly contrived arrangement of masses would be needed to produce significant effects.)

7. Basing inertia on an energy field will have to deal with circularity problems, since inertia is energy, and an alternative formulation if available might be preferable. (Notice that Einstein’s 1912 paper, as in (1), suffers from defining $m$ in terms of $m$’s.)

Five of the seven points are based on careful empirical results, following Maxwell’s lead in method of laying the groundwork for a theory, and there is some empirical evidence at least for the frame dragging portion of point six. But of course, we still have the feeling we have no idea how inertia works, because we have become accustomed to understanding the workings of things in quantum terms.

VI. Exploratory Ideas in Quantum Inertia

One may start with inertia or gravity, we argued at the beginning. The road of starting with gravity, providing a quantum formulation, and deriving inertia with an induction-like procedure is well traveled – even if the parts of the road are unconnected and no one can be sure they have reached the destination. With this path the reader is likely to be familiar. And numerous investigators have argued based on isotropy that this road is at least difficult, even if a quantum formulation of gravity is at hand. So we will now survey the other road, that of quantum inertia.

An electromagnetic interaction with the vacuum field was proposed as the source of inertia in 1994 by Haisch, Rueda and Puthoff [27], based partly on an old idea of Sakharov. It is necessary to suppose that matter is “ultimately made of subelementary constitutive primary charged entities or ‘partons’ bound in the manner of ... Planck oscillators.” The derivation is mathematically complex, but using a Zero Point Field (ZPF) based model of Newtonian gravity, it is claimed the concept “suggests a physically rigorous version of Mach’s principle.”

In a 1999 progress update [28], reporting on the results of a NASA funded study, the theory was been extended to cover the relativistic acceleration law, and it is anticipated the analysis will be extendable to more general versions of the quantum vacuum than just the electromagnetic one. The authors are still active and new papers appear occasionally. The impetus, obviously, is that a detailed quantum theory of inertia based on vacuum energy, especially electromagnetic vacuum energy, might provide some hope of manipulating inertia, and thus the interest from NASA. One of the authors, Puthoff, has formed an institute that seeks to apply vacuum energy in other ways, and to control gravity. The names of these authors, along with Sakharov, are used by Arthur Clarke in 3001: The Final Odyssey as inventors of a space drive which cancels inertia. The name of the drive is SHARP, an acronym based on the authors’ names.

As one might expect, such a large diversion from well established theory (only achieving compatibility with special relativity in 1999, and no thought yet as to GR), with an eye already to applications, and memorialized in fiction, has not endeared the group to academics or promoted a consensus. But the effort is commendable in that it is in many ways more tangible and testable than quantum gravity theories.

Woodward, also a proponent of inertia manipulation and of actively thinking about and working on novel means of interstellar travel [29], rebuts Haisch-Rueda-Puthoff based on equivalence. He says:

“...the coupling of electric charge to the electromagnetic field cannot be made to plausibly mimic the universal coupling of
gravity and inertia to the stress-energy-momentum (i.e., matter) tensor.” [30]

It is obvious, then, that Woodward, though trying to manipulate inertia, is using GR as a starting point. This would be fine if a good quantum connection between GR and inertia existed, but it does not.

However, Woodward correctly points out the difficulty that must be overcome if one proposes to start with inertia and not pre-suppose GR. (If one pre-supposes GR, as we have seen inertia is a consequence and does not admit a fresh look without the burden of quantum gravity.) Namely, that difficulty is the equivalence principle.

The linkage between equivalence and the curvature of space-time which inevitably leads to GR is a convincing argument, but according to Clifford Will, a leading authority and NASA consultant on the verification of GR, it is not a proof [31]. To follow the approach of inertia first, then gravity, one should start without GR and even without equivalence and judge progress by whether these (or something like them as far as experiment goes) will emerge.

**VII. Quantum Metric Fields**

A very recent and promising development involves an alternative formulation of quantum fields as measurement (or position) based rather than energy based [32]. The uncertainty principle can be written in terms of time and energy, or in terms of position and momentum (and various other quantum complements). There is no theoretical reason to use one or the other. But by historical tradition, and because of its runaway success, the time-energy formulation is the one used in traditional QM. We could sum it up by saying that the field is interpreted as energy, and in short periods of time the uncertainty of energy is sufficient that virtual force-carriers (bosons) appear and do the work of the field via momentum transfers.

We have already pointed out (point 7), that starting with energy to define energy is less than desirable. Indeed, in cross-frame measurements, energy is not even a conserved quantity, it is subject to transformation laws [25] as is the ticking of clocks and the wavelength of light.

Momentum is conserved in cross-frame transformations [25], even though momentum is, as we usually define it, a composite of mass, time and position (rate of change). And so [32] posits a field based on momentum-position uncertainty. Applying suitable assumptions, the uncertainty relation is rearranged to express mass in terms of the reciprocal of the uncertainty of position.

The reciprocal of a position (distance) measurement immediately suggests the 1/R of potential formulations. And so [32] suggests a “quasi-measurement” field in which particles in some way measure each other. Initially without mass, they can be out of position by an unrestricted amount, and by directly interacting with each other, rather than through an intermediate energy field, they determine each others’ position more accurately. The limiting of the possibilities of position is exactly what inertia is. Inertia is the inability of matter to be “out of position” spontaneously. The more inertia, the more work has to be done to get a mass to change its state of motion, its position and velocity.

The details of the arguments in [32] are beyond the scope of a survey paper, and it has not been available long enough for responses to appear. Suffice it to say that equivalence is obvious, since the uncertainty relation applies to any kind of particle, and all fields can manifest as particles when quantized. And that the mathematics of light bending and precession and many other features of GR are obtained.

Since time is a function of inertia, and inertia and therefore time are determined by the quasi-measurement field, i.e. by the configuration of other matter-energy much as in GR, there is an analogy between time in this theory and the coordinate time in GR.

Gravity emerges from quasi-measurement fields because the quasi-measurement process is supposed to be ongoing, like a series of measurements. When a particle is “re-sampled” it may be found slightly higher or lower in a in the field surrounding a nearby massive object. If lower, its inertia is greater and its position uncertainty is less, and it cannot with equal likelihood return to its
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former position. Suitable assumptions about the rate at which re-sampling occurs can produce gravity, specifically gravity which matches important empirical properties of relativistic gravity. Indeed, the fluctuation in the spatial uncertainty of particles reminds us of the curvature of space, even if it is not the exact same mathematical formulation. Striking advantages of producing gravity this way are that its weakness is easily explained, and intractable renormalization is avoided.

Because of the analogy of the transformations of time and spatial uncertainty in the theory of quasi-measurement fields and their roles, with the role of space-time curvature in GR, I have given this section the heading “quantum metric field.” More work is required to illuminate the extent of similarities and differences with GR, and the degree to which empirical observations of cosmology can be accommodated.

One surprise result of this very directly Machian theory is that point 3 of Einstein’s features of Mach’s principle, and Mach’s view of what happens if the universe rotates about a bucket, are not upheld. Consider a droplet in a rotating bucket of water. At a given instant, this droplet sees:

1. The rest of the universe instantaneously traveling linearly opposite to its tangential motion,
2. The rest of the universe accelerated opposite to its centripetal acceleration, which is at right angles to its tangential motion.

The droplet experiences inertia opposite to the centripetal acceleration. So far everything is normal. Now consider the case of the universe rotating about the bucket, and what the same droplet sees:

1. The rest of the universe is instantaneously traveling in all directions,
2. The rest of the universe is instantaneously accelerated in all directions.

The summation of the back reactions to the accelerations do not add to very much of anything, just a tiny frame drag owing to the droplet’s offset from the center of the universe’s rotation, and in the wrong direction to uphold Mach’s view that rotation of the universe would have the same effect as rotation of the bucket.

VIII. Conclusion

We have overviewed a century of troubled but gradually progressing understanding of inertia as it relates to gravity. There definitely is a relation to gravity; boundary conditions may not be as important as was thought when astronomy was limited; inertia is isotropic which disadvantages the induction theories; and further understanding of inertia in terms of gravity is likely problematic until quantum gravity is understood.

An interesting recent development is to try and formulate inertia from quantum principles, independently of gravity. Two methods were surveyed, one of which takes full advantage of existing QM techniques but has much work to do before it can satisfy equivalence. The other method easily satisfies equivalence, but requires an unexpected reformulation of quantum fields and has not-yet-explored implications for quantum measurement and cosmology. The former method promises the possibility of manipulating inertia, and the latter would seem not to hold much promise for manipulation since there is no obvious way to manipulate the quasi-measurements.

Both proposals are immature, and have, at least initially, progressed faster and farther and appear more testable than traditional quantum gravity theories. The quasi-measurement proposal also depends heavily on newer interpretations of quantum waves and measurement.

Quantum gravity may remain the holy grail of physics for some time. Despite complexity, it is less disruptive to other branches of physics. But quantum inertia is showing strong “potential” to make an end run around it.

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