Unruh effects, Hawking Black Hole Evaporation, Quantum Corrected Larmor Formula, Numbers of Particles in Curved Spacetime: “Same-Same, but Just A Bit Different”

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Abstract

This paper explains the origin of the Unruh Temperature, in terms of disagreements, on the number of particles encountered between accelerated and inertial observers, and relates it to the conventional approach of Unruh accelerated detectors. It is not a new explanation.

However, we argue that the same explanation applies to justify why (massive) accelerated charged particles radiate, leading to the Larmor formula, including its QED versions. We contend that not just the quantum corrections, but also the classical part, are just equivalent to the Unruh effects. It also explains why Hawking black hole radiation includes contributions both from particles escaping on the black hole horizon, and from particles created, by spacetime curvature changes, between the horizon and the asymptotic infinite away from the black hole. It is also why observers can’t agree on the number of particles present in a curved spacetime.

The use of these phenomena to explain the full Larmor radiation formula, and the Hawking radiation derivation options may not be widely known. In fact, at the difference of recently published popular science articles about alleged first observation of Unruh radiations, the present paper argues that Unruh radiations have been observed from a long time: whenever an accelerated (massive) charged particle radiates, like for example in a radio source, antenna, or oscillator. In fact, the Larmor radiation can be extended to any Yang Mills interactions for accelerated massive particles, based on the Unruh effect. It has consequences on particle decays, with now the possibility for example that an “accelerated proton” decays due to the Unruh effect. We ruled out such decays in an inertial frame, but when accelerated, it is possible, and it still does not support GUTs.

The paper also introduces the notion of Larmor gravitation radiation, that it exemplifies with frame dragging General Relativity (GR) effects, and the universe spacetime memory. It is then extended also to all the other interactions: QED, QCD, Electroweak.

As a digression, we conclude that radiation when electron jump down to a lower level of energy in an atom are also Larmor radiations. Similarly, we present some considerations on the Schwinger effects and its relation to all this.

We conclude with some multi-fold universe considerations, based on the microscopic composition of the spacetime of multi-fold universes (massless Higgs boson, including why gravity and entanglement break the Reeh-Schielder theorem.

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1. Introduction

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A recent paper renewed the interest in the Unruh radiation [6] with proposals to finally be able to observe it with tabletop experiments [1]. Maybe fueled by the envisaged link to warp drive glows reminiscent of Star Trek, popular articles have presented the paper by arguing that Unruh radiations has never been observed [2-4], and that such tabletop experiments are the first opportunity to see them. Based on our (microscopic) interpretation of the Unruh effect, we have some difficulties reconciling such interpretation with such a statement. Indeed, we argue that the Unruh effect is also at the origin for the (classical [6-8] and quantum [9]) radiation of (massive) accelerated charged particles, including for the classical Larmor formula [5], which is a conclusion different from [8], which attributes Unruh effects only to Quantum corrections. [97,*159*] relates to, and explains, conventionally and in multi-fold universes, the different order of radiations, to / as classical versus quantum contributions. But, in this paper, we will all see that all effects are quantum, even if Larmor effect at its lowest order can be predicted from the Maxwell's equations / electrodynamics [5]. *Note added on August 19, 2023: In the remainder of the paper, references in italics have been added on August 19, 2023.*

In our paper, the Larmor radiation becomes a property of any accelerated massive, charged, electromagnetic, but also Yang Mills, particle or object, even if it is in practice dominated by electromagnetic effects. This has significant implications for the decay of accelerated massive charged particles like accelerated protons. We are not sure how widely known these observations are, besides say [10], who are more focused on arguing for the existence of the Unruh effect.

Also, we had already argued against the view in other popular science articles [11], that Hawking's proof of black hole evaporation by Hawking radiation [12-15] would, in some cases, be incorrect [16]. It turns out that the two contributions matter contribute, and can't be easily separated even if both can be used stand alone to derive the law radiation law. *Note added on August 19, 2023: More considerations have been presented in [147,148].* They are: (i) the picture of particle pair generation at the black hole horizon, with capture of one of the particles [13], and (ii) the account of the particles curved by the curved spacetime between the horizon to the infinite [14,15].

We relate the discussion to the Schwinger effect [*147,148*].

To complete the picture, the microscopic explanation of the Unruh effect implies ambiguity across observers who can't agree on the number of particle present in a curved spacetime [16].

{HERE} Note added on August 19, 2023: Interestingly, the Larmor radiations also occurs with gravitation, as exemplified by GR's frame dragging [130,155-158]. This allows us to predict memory effects for gravity, as reported, and discussed, in [160-169] and references therein, and in fact for all fundamental interactions. Our presentation offers way simpler explanation than what is currently presented in the literature, to argue such effects [169-171].

We conclude with a brief discussion of how the Unruh effect appears in multi-fold theories [17-20], the impact on microscopic aspects of spacetime and the Reeh-Schielder theorem [46], already known to be violated by gravity and entanglement [17].

2. Unruh effect

The conventional Quantum Field Theory (QFT) interpretation of the Unruh effect [6,21][2], or Fulling–Davies–Unruh effect, predicts that an accelerated detector will observe a thermal bath, i.e. the vacuum appears as excited to a

[2] Several people actually discovered the Unruh effect. It is why it is also sometimes referred as FUD effect or Fulling–Davies–Unruh effect [6]. In this paper, for simplicity, we only speak of the Unruh effect.

non-zero temperature proportional to the acceleration. The Unruh radiation is the resulting radiation. The Unruh temperature seen by an accelerated detector is a well-known effect, well accepted, but the associated radiation seen in an inertial frame is argued has never been observed, and criticized by some, the latter on the basis that absorbed and emitted radiations in the detector would compensate each other [22]. As we will see the latter is not correct.

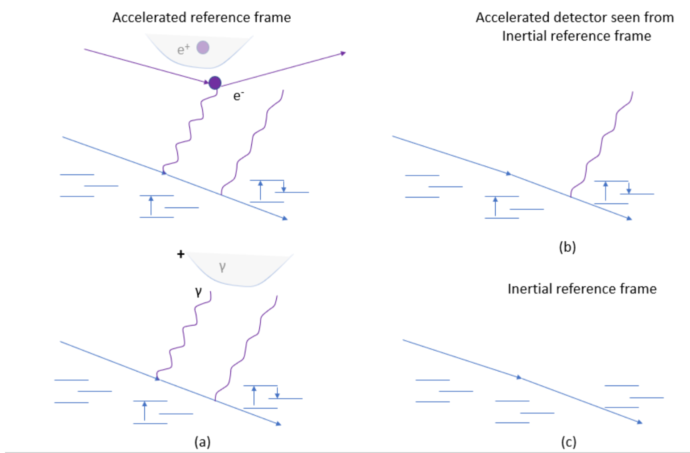

Figure 1: The Unruh effect, (a) detected in an accelerated detector. The gray shaded region symbolizes the region beyond an horizon for the observer due to its acceleration. (b) shows the accelerated detector seen from an inertial reference frame. It radiates when it detected a particle. This is associated to the energy level jump down of the charged electrons, which corresponds to an acceleration of the electron, hence arguably a Larmor radiation. (c) shows a non-accelerated detector in an inertial reference frame: it detects nothing (except for quantum fluctuations). In all the figures the total contributions results from the path integral combining all the configuration possibilities.

Our explanation of the effects, provided in figure 1, resolves the existence of Unruh radiation questions: there is radiation in the accelerated reference frame due to the temperature, and in inertial reference frame, and we will see that it is a Larmor radiation as will be discussed in section 3.

Of course to be able to be in an accelerated reference frame, the accelerated system must be massive.

Accordingly, consider an observer in an accelerated reference frame. Whatever constitutes spacetime, or QFT vacuum, as seen by another observer in an inertial reference frame, will appear receiving energy or excitations from an apparent force producing the relative acceleration (any reference point[3] on spacetime appears accelerated relatively to the accelerated observer in that observer's reference frame). In the QFT vacuum this can only be modeled by new particle pairs, or excited particles. Such pairs involve particles and anti-particles that can be charged, or colored. Per QFT construction, these effects are Lorentz invariant. So the vacuum remains the same even across Lorentz boosted reference frames: only accelerated observer encounter excited vacuum (in flat spacetime).

Note however that the explanation, given so far for figure 1, is incomplete: because the accelerated observer moves faster and faster, a portion of spacetime progressively disappears behind an horizon, beyond which it would

[3] Of course, in conventional General Relativity (GR), spacetime is not a "real" entity or object. Yet particles in the QFT vacuum, when they are created in pairs by quantum fluctuations, can be seen as such temporary references. The multi-fold spacetime, as discussed in section 6, may offer better reference points if the reader is uncomfortable: the discrete concretized spacetime location occupied by massless Higgs bosons [17,47,64,a15,b59,b60].

require supra luminous exchanges to otherwise exchange interactions. Some pairs of particles and anti-particles have one of them disappear behind the horizon, so that when examining all the possible configuration of figure 1, which is what the path integral behind the processes does[4], the balance gives an excess of particles that are the ones that matter. All are engaged In the process of figure 1, but all the others (both pairs exists on the side of the horizon where the accelerated observer is) have canceling effects (e.g. positive and negative charges)[5].

Rigorous derivation in flat and curved spacetime can be found, for example, in [21], for uniformly accelerated observers. The excited vacuum, implies a non-zero temperature. The Unruh temperature seen by the accelerated observer is proportional to its acceleration. Figure 1 also implies immediately that the Unruh temperature will be proportional to the acceleration of the accelerated observer[6].

Unruh and De Witt proposed a detector as shown in figure 1 [6,23,24]. It detects a thermal radiation of Unruh radiation proportional to its acceleration with respect to a inertial reference frame as shown in figure 1(a). It is abstracted as a system excited by radiations. Excitations are detected when the detector itself radiates, when returning to a lower energy level.

Figure 1(b) shows the accelerated detector, as seen from an inertial reference frame: it must reflect the detector radiation when relaxing, or we would have fundamental inconsistencies between observers who would not count the same number of detections. Yet, the inertial observer does not see the incoming vacuum radiations from the thermal background, and the associated created pairs of particles and anti-particles. The radiated photon associated to the jump down to a lower energy level can be seen[7] as an acceleration, with a Larmor radiation as discussed in the next section. We believe that associating the radiation by electron jumps down level in atoms to Larmor frequency is a first.

The illustration from this section does not restrict the analysis to uniform acceleration, or Killing fields, in Rindler wedges, as envisaged in [21]. There is nothing special about these, other than the ease of computation with such models, and/or with uniform acceleration.

3. Larmor radiation, Larmor formula: radiation of an accelerated charge

[4] The figures in this paper are not exactly Feynman diagram, but the Feynman diagram associated to them, again envisage all possible configurations.

[5] It really shows how critical is the horizon in encountering an Unruh effect and radiation. It is also such considerations that ensure that radiation takes place, and that arguments as in [22] are not correct.

[6] Indeed, ΔE seen by an accelerated observer can be approximated as: $\Delta E \propto F \,.\, x \propto m \,.\, a \,.\, x \propto \frac{E}{a}$ (1). Based on thermal field theory (statistical physics correspondence), equation (1) means that temperature $\propto$ a, for constant acceleration, as obtained in [22]. The result here however is generic for a given acceleration.

[7] Yes, it is a radiations to the electron jumping down energy levels, which accelerates it. It is interesting though to see that this a particular (extreme) case of quasi-instant acceleration (which is rather smooth per [25] (part 5) and [26-30], [26] is maybe the most intuitive for the public). We reference so many papers because these papers details may not be that widely known. However, none of these equate then the associated emission with Larmor radiation, which it is. The irony is not lost that Larmor explicitly identifies the Larmor formula as challenging the Rutherford atom model, and that the Bohr atom model and Quantum mechanics was introduced to address this issue, among others. And now, we argue that the Bohr atom actually radiates Larmor radiations, but only at the time of electron jump down (jumping up it absorbs radiation, i.e., a photon, which could be seen as a negative Larmor radiation due to deceleration).

Our discussion in the previous section has already divulgated what we will say. No surprises anymore. We spoiled the fun for everyone.

3.1 QED / Electromagnetism

Let us consider the radiation of an accelerated charged particle as illustrated in figure 2.

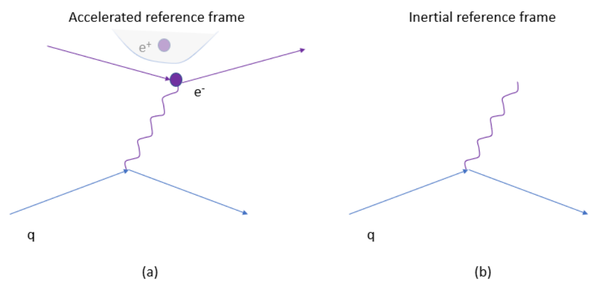

Figure 2: It explains the (first order) radiations by an accelerated charged particle using the Unruh effect. (a) corresponds to an accelerated reference frame that sees virtual pairs of particles that can interact with the accelerated charged particle q via exchange of virtual photons. The gray shaded region symbolizes the region beyond an horizon for the observer due to its acceleration. (b) shows what is seen by an inertial observer: the particle radiates, and the excited vacuum of (a) is not seen. In (a) and (b) the total contributions at this order results from the path integral combining all the configuration possibilities. This applies to all the figures in this paper.

Interestingly, figure 2 provides the explanation and justification for electromagnetic radiation by accelerated charged particles also known as Larmor radiation and the associated Larmor formula[8] [5]. A relativistic extension[9] exists based on the Liénard–Wiechert potentials [5,33].

The effect is very neatly modeled in [9]. However, [9] introduces a different terminology: Larmor radiation as the classical contribution [6-8] and Unruh effect for the quantum correction. We dispute that view. Indeed the computations in [9], treat both contributions exactly the same way, just separating at the end to recover the classical terms, and then consider the corrections. In our view, it means that both contributions are Unruh effect, including the classical one. They both are because they both result from the QFT effects of particle and antiparticle pair creation shown in figure 2(a). Without it, the contribution in figure 2(b) would be null. This invalidates the classical vs. quantum distinctions of [9]. It is quite different from [97], where the notion of order of radiation is explained in ways closely related to radiations.

On the other hand, the fact that [9] also equates Larmor and Unruh as (albeit in their case distinct) contributions to the same phenomena supports our approach and model.

Figure 3 and 4 sketch some second order contributions, i.e. the second order corrections, that [9] denotes, incorrectly per the above, as quantum corrections.

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[8] It also relates to Compton scattering [31].

[9] Nothing changes in principle and as already justified by Lorentz invariance of QFT, only accelerated charges radiate also in the relativistic case.

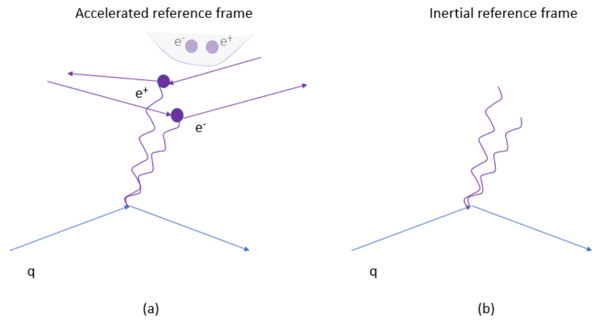

Figure 3: One type of second order corrections to the radiation of a charged particle, due to the excited vacuum. The gray shaded region symbolizes the region beyond an horizon for the observer due to its acceleration. In (a) and (b), the total contributions results from the path integral combining all the configuration possibilities.

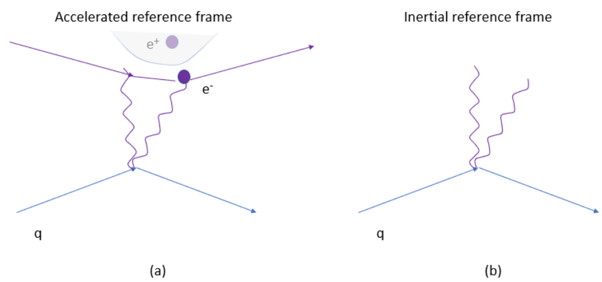

Figure 4: Another type of second order corrections to the radiation of a charged particle due to the excited vacuum. The gray shaded region symbolizes the region beyond an horizon for the observer due to its acceleration. In (a) and (b), the total contributions results from the path integral combining all the configuration possibilities.

With figure 3 having opposite effects, and larger contributions, than figure 4[10], we expect that the correction will reduce the Larmor effect with respect to the classical contribution. That is indeed what has been report [9,32]. Cases where the contributions of the corrections is constructive should be seen as resonances with the background field, or amplification due to the medium.

3.2 Electromagnetic radiations by an accelerated charge is an Unruh effect

The conclusion is clearly that Larmor radiation, i.e., the radiation by accelerated (massive)[11] charges is a manifestation of the Unruh effect. It has been observed and harnessed in all radio, antenna and wireless applications[12]; we observe the Unruh effect and rely on it every day of our lives [7,8].

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[10] And a smaller contribution than figure 2.

[11] "Massive" matters because one can't be the reference frame of a massless particle, as already mentioned. However that statement is a tautology as a massless particle can only propagate at *c* in the vacuum. Yet, change of direction of a massless particle, e.g. due to gravity bending/lensing, could result in radiation, possibly discrete in a Both-like bound state, as we have already discussed.

[12] The point of view of [9] would disagree, and argue that this is just the Larmor effect. We understand the terminology issue, but as already mentioned we disagree; even the classical contribution is due to the Unruh effect.

In fact, the paper [1], at the origin of the flurry of article on the Unruh effect, is very similar to [9], and so, ironically[13], the proposed tabletop experiment to detect Unruh radiation, is in fact arguably a Larmor radiation. They are the same, just arbitrarily categorized differently. As we explained, [9] can involve medium or background electromagnetic field that produces constructive interactions of the effect with the electromagnetic field (photon bath), to produce cases where the corrections amplify the effect [1,2].

You will also note that our model is generic. Nothing limits this discussion to uniformly accelerated charges as typically computed in lectures and papers. There is nothing special about uniform acceleration other than simplifying computations and models.

We would argue that the explanation presented here is more fundamental as QED explanation, vs. relying on the classical understanding of Larmor and its relativistic extension [5,33], which in any case cannot account for the quantum corrections. Yes, [9,32], and related papers, provide detailed computation, but we argue that somehow it lacks the simple physical explanation conveyed by figure 2.

3.3 Yang Mills Larmor radiations and the decay of accelerated particles

The discussion of section 3.1 applies equally well for any charged / colored particle like QCD, the weak, or electroweak interactions. Of course, in the case of QCD, other effects appear related to color asymptotic freedom and confinement that prescribes that only dipoles effects could exist at best [34,35]. Also for the weak interaction, we need to consider the limited range resulting from the massive weak interaction bosons.

Figure 5 illustrates the case of the weak interaction, and the accelerated proton decay.

We have argued in [17,36], that proton decay does not take place, except, maybe, in some black hole situations. We stand corrected. There is another case where it may take place: accelerated protons may acquire enough energy to decay as shown in figure 5(b). We see that, with the Unruh effect, it is actually the result of interactions with excited vacuum instead of a decay. It remains consistent with [17,36], except that we did not qualify "non accelerated".

It is a very important result, even if not new, that accelerated particles may alter their decay options versus no accelerated ones. We do not believe that it is as widely known as it should be, especially when discussing proton decay.

Because it is actually the result of interactions, such a proton decay example does not invalidate our previous work [17,36] (it is a loophole to the smearing effects due to gravity presented in [17,36]), and it should not be considered as cases of observation of conventional[14] proton decays that are aligned with predictions of theories like Grand Unification Theory (GUTs), or superstrings and supersymmetry, but have never been observed so far. It still looks that the absence of observation of any conventional proton decay is a death knoll for such theories [17-20,37]. And our past reasoning continue to imply that no such decay will be encountered. *Note added on August 19, 2023: See also [70,98] for a proof why no supersymmetry exists in a 4D spacetime with a positive cosmological*

[13] In case we need to explain the irony. Popular science articles argue that Unruh radiation would never have been observed [2-4], while the Larmor radiation is observed daily. Yet the tabletop experiment that they refer to as a way to see Unruh radiation would in fact show the Larmor radiation. And as that would involve both what [9] presents as classical terms, and quantum correction. But that confusion is not removing the contradiction.
[14] That is, in an inertial reference frame.

constant. It is based on modeling QFT with quantum cellular automata, i.e., random walks as proposed in [17]. See[61,141] and references therein.

Note also that every particle[15], including even the totally neutral Z^0 boson, if non-massless[16] and accelerated, will have Larmor radiations as generalized here, even the left-handed neutrino. Accelerating the neutral Z^0 boson is non-trivial. It would require a gravitational field, and result into with gravitational wave radiation contributions[17]. Unfortunately, most of these generalized Larmor radiations are not any close to being detectable, yet, as we just saw, they have a major impact on the Standard Model (SM), in terms of decay of accelerated particles, especially the proton.

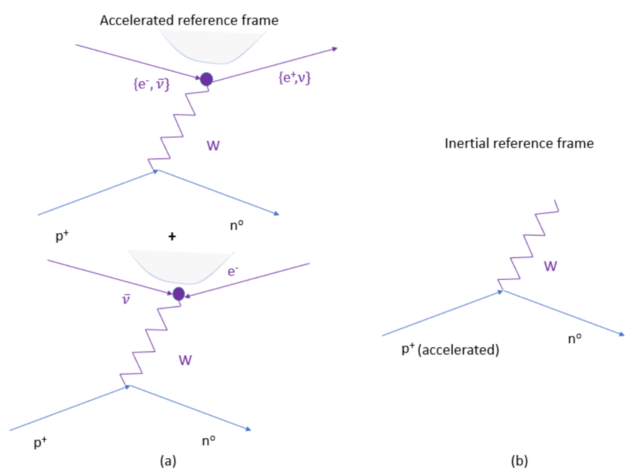

Figure 5: Larmor radiations for the weak interaction and implications on accelerated proton decay, as a consequence of the Unruh effects. The gray shaded region symbolizes the region beyond an horizon for the observer due to its acceleration. In (a), and (b), the total contributions results from the path integral combining all the configuration possibilities.

4. Ambiguity of the number of particles in a curved spacetime

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15 Except the right-handed neutrino, if it exists, where the story is more complicated [17-20,38,39].

16 As we can hitch a ride on a photon, at least if massless, i.e. outside for example superconductors where symmetry breaking may endow it a mass [40-42], à la Higgs – the original mechanisms proposed by Anderson, we can't encounter Unruh effects for photons, and, therefore, no photon Larmor radiation (Higher order photon correction may involve photon radiations, e.g. from fermion triangles, but these are addressed by renormalization and not the Unruh or Lamor effect). (*Note added on August 19, 2023: See also [153]*).The same holds for massless gluons, even if bi-colored, and able to emit gluons: one can't hitch a ride on them, in addition to the confinement and asymptotic freedom challenges (unless again if the acquire mass under confinement conditions, which is actually usually the case per [35]). Gluon balls could also have Larmor radiation due to Unruh effects as they are massive [35].

17 We speak of microscopic wave contributions, instead of gravitons, because in our multi-fold theory, and inspired by it, gravitons are not physical in spacetime, at least as particles [17-20,43,44].

It is well known that different observers in a curved spacetime will not agree on the number of particles that they see, and the number may even be infinite. For example, a conventional derivation can be encountered in [45].

With the Unruh effect, it can be explained as follows: two observers in different reference frames will obviously see different numbers of particles unless the reference frame are Lorentz transformed (which they can't globally be in a curved spacetime, unless if only infinitesimally separated). QFT is designed to be compatible with special relativity, and the vacuum state is Lorentz invariant[18]. it means all observers in constant motion in flat spacetime will agree what the vacuum state of the field is. As the vacuum state is not invariant in curved spacetime, in a curved spacetime, different observers will disagree about how many particles are present, and therefore will disagree about the vacuum state. At different locations in spacetime, observers will see different numbers of particles. And if particles are themselves accelerated because in a curved spacetime, they will further radiate.

Furthermore, we know that disturbance in gravitational fields produce particles. See for example [45,48].

All these are additional arguments conventionally presented for claiming that particles are not physical, but just quantum field excitations; the quantum fields being fundamental. In [1,49], we argued against such views, and linked it to the challenges in modeling quantum gravity with QFT[19].

Here, we maintain that view: particles can be created and destroyed by different processes, and they may be real or virtual. Their visibility in certain reference frames results from some virtual particles becoming real in other reference frames. It means that physical versus virtual is rather an artificial distinction, due to the reference frame of the observer, and analyses, which argue that virtual particles are only a mathematical artefact, can be argued against as in [17,49], and now also because of the ambiguity that we just discussed: their nature change from reference frame to reference frame.

The Unruh effect is everywhere, and per the principle of equivalence[20], it appears in curved spacetime through the ambiguity of the number of particles seen by observers in such spacetime (acceleration creates disruptions) and particle creations (by disruptions), as well as the Hawking radiation (see next section): they are different facets of the same thing.

Yes one can still argue that it means that particles, real or virtual, are therefore non-meaningless. But we have argued against that view in [17,49], and Unruh effects so fundamental to QFT, is actually best explained as in figure 1, … with particles.

Throughout many papers, tracked in [17-20,*118,152*], we have argued that in the multi-fold theory, particles, including virtual particles are a key aspect of the multi-fold theory and something that QFT should revisit. *Note added on August 19, 2023: See also [35,61,98,141,150,151] for the subsequent arguments that particle random walks are actually equivalent to QFT.*

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[18] We can't resist stating the following: multi-fold universes break the Reeh-Schielder Theorem [17,46], if one accepts the results of [47,*148*], that indicates that GR-based gravity is multi-fold, then one understands that gravity, and entanglement could result into different vacuum at different locations, and for different observers. This also addresses the question in [46] about entanglement, and the Reeh-Schielder theorem. The answer is no, as currently formulated in conventional QFT: the theorem is not the equivalent to entanglement for QFT. We did not discuss explicitly such a result in [17]. *Note added on August 19, 2023: See also the discussion in [128].*

[19] Indeed, without particles, entanglement is not well modeled in QFT, as also corroborated by the question in [46]. The multi-fold theory shows that entanglement produces gravity like fluctuations [17,50], and that gravity results from entanglement. It is the factual E/G conjecture in multi-fold universe [51], and a tempting conjecture for our real universe, considering [17-20,47,*147,148*].

[20] See [17,52] and references therein for discussion of the principle of equivalence in QFT, and multi-fold theory.

5. Hawking radiation and black hole evaporation

5.1 Hawking Radiation, business as usual

Therefore, it is no surprise that we will argue that the Hawking radiation effect behind black hole evaporation [17,12] is also the result of the Unruh effect, where the horizon results from the black hole instead of the acceleration of the observer.

A pair of particle and anti-particle near the black hole horizon can have one particle escape, while the other one is captured behind the horizon. If we compile all the possible configurations, charged opposite configurations will cancel charging the black hole horizon. So, not interaction occurs due to a charge with the black hole when a charged particle is captured. Schwinger effects are mentioned later on [*146,147,172*].

As the companion particle escapes, it can itself radiate due to its own acceleration, or deceleration. But overall, when considering all possible configurations, that contribution will also cancel with say the one from an opposite charge. Pure Larmor radiations are cancelled out.

As a particle escapes, the black hole mass decreases. Per the previous section, this also contribute to creating additional particles in the curved spacetime[21]. More particles appear between the horizon and the infinite. Among those some are seen to escape by an inertial observer at the asymptotic infinite away from the black hole

It is sketched with figures 6 and 7.

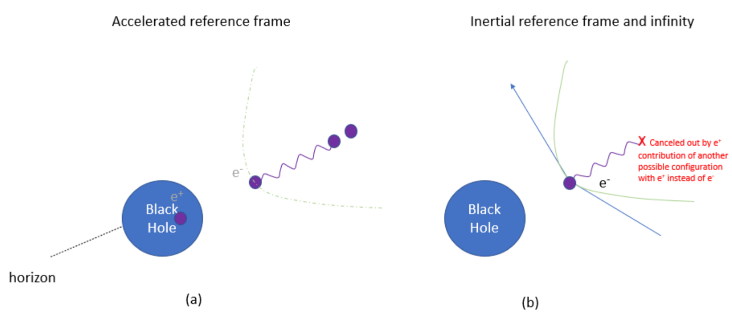

Figure 6. (a) the black hole captures behind its horizon one of the spontaneously created pairs. The other particle escapes, which means acceleration on an orbit. It may radiate, if charged. Switching the configuration (e.g. positron escapes instead) cancels the charge on black hole horizon and the Larmor effect. Only the escaped particle matters when it comes to computing the total radiation escaping to infinity, where it can be observed by an inertial observer (b). In (a) and (b), the total contributions results from the path integral combining all the configuration possibilities.

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[21] The gravity field created, by the black hole, is perturbed by that loss, and the black hole contracts as it loses mass/energy [17,53].

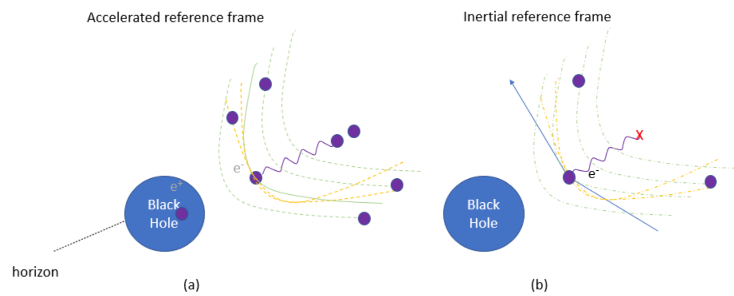

Figure 7: As a particle escapes, it changes the mass of the black hole, which, in turn, creates spacetime perturbations, which produce particles, some seen by the inertial observer. These are the only other ones that matter. In (a) and (b), the total contributions results from the path integral combining all the configuration possibilities.

The Hawking radiation and black hole evaporation is the sum of all the particles observed at infinity in figure 7(b).

Note that, if we consider all possible configurations in figure 7(a), from all the possible configurations in figure 6(a), we see that all weighted (by their probability) sums of all possible options in 6(a) can match figure 7(a) (possibly changing the weights to reflect different normalization, for each of the different options)[22]. Or we can just pick one and change the weight. It amounts to the same when normalizing everything.

In other words, there are different ways to obtain Hawking radiation as was already found by Hawking in his different publications [13 -15] that contains these different approaches. One comes from the radiation at the black hole horizon, it is the traditional image of pairs of particles and anti-particles, with one escaping while the other is captured[23] [13], the other results from outbound particles produced between the black hole horizon and the asymptotic infinite [14,15]. They match looking at mostly figure 6, or mostly figure 7.

Funnily, these different matching derivation resulted into some popular science controversies that Hawking would have lied in his teaching of the effects [11]. In [16,*144,145,147*], we dispute such a view: both contributions are valid and not really separable, i.e. we picked figure 6 [24] + figure 7.

Physically though, it is clear from the above that the combination of both, as argued in [16,*144,145,147*], is the correct microscopic explanation, even if the mathematics are ok with just picking one option: some radiated particles come from the horizon capturing particle, and some come from the evolving spacetime curvature, throughout the history of changes of the blackhole, that creates particles. *Note added on August 19, 2023: In [147], we provide additional arguments on the better suitability of the evaporation at the horizon. Also, for low energy Hawking radiated photons, the uncertainty associated to the large wavelength already spread the phenomena beyond the horizon, another reason why the two approaches, or any combination, can be seen as equivalent.*

Once we understand, it makes sense, it's all the same mechanisms as the Unruh effect and the equivalence principle.

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[22] The only concern might be that figure 7 does not impact the black hole. It does! Indeed, a General relativity solution like the Schwarzschild black hole, used to model such a black hole, extends to infinity. Any loss of mass or energy within the whole spacetime, reduces the radius of the horizon. It is also why losing particles from the horizon, or from the region beyond can amount to the same, even if microscopically harder to justify.
[23] It is also the approach that we used in multi-fold universes [17,53].
[24] So, [17,53] rather focused on the option à la figure 6, as we were rather intent on recovering the area law for the entropy. Again the correct microscopic approach is figure 6 + figure 7, as in [16,*144,145,147*].

The result in the present paper can be seen as detailing [16]. And the Unruh effect can be seen as the equivalent principle pendent of the Hawking radiation, for such use cases.

Note added on August 19, 2023: (This was already discussed in [146,169,173]. [169] dates back to 2021, but it was never published as a paper, other than in [152]).

5.2 Beyond Hawking radiation and Black Holes: Schwinger effects and its gravitational counterpart

As discussed in [134,146,173], Schwinger effect complements, and can at time even dominate, charged black hole evaporation. [147] provides a detailed discussion of the Schwinger effect and its gravitational generalization, with black holes and in the presence of horizons.

5.3 Gravitational radiations

As we have related Unruh, Larmor, Hawking, Schwinger and particle generated by spacetime changes, we can now predict that accelerated masses will radiate gravitational waves / propagation of gravitational perturbations. Interestingly, conventionally, this has been extensively shown, and discussed in recent articles about some new and rediscovered papers. Probably, because these effects are typically very weak and barely detectable only in the case of black hole mergers and binaries, these papers focus more on the resulting memory of the universe, and spacetime, as a result: after the perturbations pass, spacetime and things in it remain changed vs. before [160,164]. And yes these (cosmological) events and the microscopic interpretations are also what are behind the now famously confirmed gravitational waves [174-178]. Note in particular [178] closely related to [59-61,159] and links QFT points of view and cosmological scale / GR models.

In terms of the radiation of gravitational energy by an accelerated mass, the same reasoning can take place as in the previous sections with QED, QCD, or (electro)weak interactions. In conventional QFT, (perturbative) ~quantum gravity involves gravitons as the radiated particles. The effects of accelerations are also well known in General Relativity (GR) with Lense-Thirring frame dragging effects (acceleration orthogonal to movement) [155-157], and linear frame-dragging for accelerations / changes of mass along the direction of movement [155,158].

In a multi-fold, we have already encountered the equivalent effects of dynamics of the multi-folds [17,130] to cover longitudinal and orthogonal accelerations. Just as [97] helps understand the microscopic effects behind the Feynman diagrams, [130] gives a neat microscopic understanding of the dynamic effects.

Note that only accelerated particles have all these effects. Indeed, if a particle is with a constant velocity, then one can find a Lorentz Boost to get an inertial frame where the particle does not move, and so no radiation takes place. Per the principle of equivalence, no radiation is observed in any Lorentz transformed reference frame, i.e., other reference frames.

Frame dragging can be considered as the proof of the Larmor gravitational radiation effect introduced here. And what we discussed it does not require that the graviton be physical, in accordance with the lessons from the multi-fold theory [17,43,44,97].

5.4 Memories. Does the Universe remember everything?

5.4.1 Gravitational memories

The "gravitational memory effect" predicts that a passing gravitational wave should forever alter the structure of space-time. Physicists have linked the phenomenon to fundamental cosmic symmetries and a potential solution to the black hole information paradox [160-169].

We detailed in [169] the multi-fold microscopic interpretation for this.

These effects, especially when explained as in [169], are trivially the result of the changed configuration of the source and the plus infinity propagating waves, as well as possible perturbations on the content of the universe: as a source of gravity changes, with (internal) accelerations, change of its gravitational effect propagate. They can now themselves impact other objects that change configuration (and may themselves also gravitationally radiate). When the change changes or reverts, no new radiation takes place but the impact on spacetime (other content in spacetime) remains and the original radiations continue to propagate asymptotically to the infinity (or boundary if there was a boundary to spacetime).

The particular symmetries discussed [160-169], reflect cases where the changes of the source and asymptotic wave impact result into invariant spacetime changes: everything returns as I was, expect for the asymptotic waves. Yet as son that there is content chances are that the impact on them will break such symmetries. Matter (Hadrons, radiation etc.) in our universe are such "content", whose position and velocity is affected by any source change.

The impact on sources and universe content is obvious, even if very small especially for gravity effects. While very interesting, there was no real need for all the formalisms and extra super translation symmetries to reach the memory conclusions.

5.4.2 Memories of other interactions

The same reasoning can be repeated for any interaction: change at the sources is associated to propagated perturbations that change the content and propagate to the infinity. With limited range and confinement, e.g., Weak and QCD interactions, whatever propagate to larger scales is a best dipole or higher order multipole effects, and / or limited to local changes to the content. But these count as memories too.

Confirmation of memory effects in QED and QCD can be found at [164,170,171].

Note that gluons, although massless, appear massive per the mass gap discussion presented in [17,60,109]. Only gluon balls may have a massless state over continuous spacetime, but not in a multi-fold universe.

6. Multi-fold universes

So far, all the results of this paper were obtained in a conventional universe without any need for multi-fold considerations[25], other than maybe our arguments in favor of models including particles.

We are interested to discuss any additional considerations brought in by the multi-fold theory.

6.1 Overview of multi-fold universes

The multi-fold theory was introduced in [17]. Tutorials and overviews can be found at [18-20,*118,152*] while the latest developments, updates and discussions can be found at [8].

The multi-fold paper [17] proposes contributions to several open problems in physics, like the reconciliation of General Relativity (GR) with Quantum Physics, explaining the origin of gravity proposed as emerging from quantum (EPR- Einstein Podolsky Rosen) entanglement between particles, detailing contributions to dark matter and dark energy, and explaining other Standard Model mysteries without requiring New Physics beyond the Standard Model other than the addition of gravity to the Standard Model Lagrangian. All this is achieved in a multi-fold universe that may well model our real universe, which remains to be validated.

As a summary, see [17-20] for more, the whole multi-fold theory derivation, including the introduction of SM_G, can then be repeated. And so, accordingly, in a multi-fold universe, gravity emerges from Entanglement through the multi-fold mechanisms. As a result, gravity-like effects appear in between entangled particles, whether they be real or virtual. Long range, massless gravity results from entanglement of massless virtual particles. Entanglement of massive virtual particles leads to massive gravity contributions at very smalls scales. Multi-folds mechanisms also result into a spacetime that is discrete, with a random walk fractal structure and non-commutative geometry that is Lorentz invariant and where spacetime nodes and particles can be modeled with microscopic black holes. All these recover General Relativity (GR) at large scales and semi-classical models remain valid till smaller scale than usually expected. Gravity can therefore be added to the Standard Model resulting into what we define as SM_G. This can contribute to resolving several open issues with the Standard Model without New Physics other than gravity, i.e. no new particles or forces, or with the standard cosmological model (ΛCDM) in terms of dark matter and dark energy [16-20,35-39,43,44,47,49-53,56-*154,169,173*]. These considerations hint at an even stronger relationship between gravity and the Standard Model. Multi-folds can be encountered in GR at Plank scales, in spacetime quantization starting from the Hilbert Einstein action, and in the equivalence principle of suitable quantum reference frames in relational quantum physics. Conversely, GR and Quantum physics, including path integrals, the Born rule, and wave functions, can be recovered through different paths from multi-fold spacetime reconstruction and the W-type multi-fold hypothesis. In a multi-fold universe, GR and Quantum Physics are not incompatible. They are just different facets of multi-fold mechanisms, something that neither theory can well model.

With the proposed model of [17], spacetime and Physics are modeled from Planck scales to quantum and macroscopic scales and semi-classical approaches appear valid till very small scales. In [17], it is argued that spacetime is discrete, with a random walk-based fractal structure, fractional and noncommutative at, and above Planck scales (with a 2-D behavior and Lorentz invariance preserved by random walks till the early moments of the universe). Spacetime results from past random walks of particles. Spacetime locations and particles can be modeled as microscopic black holes (Schwarzschild for photons and concretized spacetime coordinates), and metrics between Reisner Nordstrom [54] and Kerr Newman [55] for massive, and possibly charged, or colored, particles – the latter being possibly extremal), or as patterns of random walk when massless [35,*124*]. Although possibly surprising, [17] recovers results consistent with others (see [56], and its references), while also being able to justify the initial assumptions of black holes from the gravity or entanglement model in a multi-fold universe.

[25] Granted that [47,*148*], arguably renders such distinction a bit moot.

The resulting gravity model recovers General Relativity at larger scale, as a 4D process, with massless gravity, but also with massive gravity components at very small scale that make gravity non-negligible at these scales. Semi-classical models also turn out to work well till way smaller scales that usually expected.

Multi-folds are encountered in GR, at Planck scales [57,47], and in Quantum Mechanics[26] (QM), if different suitable quantum reference frames (QRFs) are to be equivalent relatively to entangled, coherent or correlated systems [58]. This shows that GR and QM are different facets of something that they cannot well model: multi-folds. With the double copy behavior of Yang Mills scattering Feynman diagram [59], we also showed that multi-folds and the E/G conjecture [51] are contained in Yang Mills theory, and that Yang Mills models gravity, as far as, a duality [59,60]. New AdS/CFT conjectures can also be derived [18]. The double copy duality also allowed us to derive that GR-based gravity is asymptotically safe [61]. The results of the theory seems to also point to the need for our universe to be multi-fold [148].

6.2 Unruh effects in a multi-fold universe

The main point to consider is that the spacetime of a multi-fold universe is essentially 2D at small scales, discrete, fractal, Lorentz invariant and non-commutative, and particles are microscopic over extremal black hole Qballs of Higgs condensates (or random walks when massless above multi-fold gravity electroweak symmetry breaking) matching 7D (essentially 5D) solitons from multi-fold space time matter induction and scattering [17,56,60,62-64,66-68,99,*124*].

When, in accelerated reference frames, the observer still sees a discrete spacetime, especially at high enough energy scales, but it sees explicitly these concretized spacetime point accelerating, which amount to have the massless Higgs associated to them appearing to gain energy, i.e. to be excited, or grouping/condensing into new solitons (solutions). Any inertial observer does not see those or the excitation of the massless Higgs. It explains the excitation of vacuum, and breaking the Reeh-Schielder theorem, something already suspected since [17]. All the conditions are satisfied to support the Unruh effects. As multi-fold universe also support the principle of equivalence [17,52], this was expected. In a continuous spacetime, even if curved, it is harder to explain how an observer notices its acceleration, other than stating that it just would.

Note added on August 19, 2023: Again, see also the discussion in [128].

7. Conclusions

Albeit a priori just a tutorial on Unruh effects, this paper presents a few interesting results or reminders.

It provides an explanation of the Unruh effect not as strongly tied to Killing fields, Rindler wedges or uniformly accelerated reference frames, as usually encountered in the literature

It links the Unruh effect and the Larmor radiation: they are the same thing. Starting from the Unruh effect for an accelerated charged particle, we obtain the Larmor radiation when seen from an inertial reference frame. This provides a nice QED justification for the microscopic justification for the radiation of accelerated electromagnetic charged particles, that formulas do not convey as well as, nor do classical computations. Also, the analysis is not limited to uniform acceleration, and recovers the direction of the quantum corrections to the Larmor radiation.

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[26] Standing in for Quantum Physics in general.

The paper shows that we see the Unruh effect every day. We also argue for Larmor and Unruh being quantum effects, without distinction of Larmor as a classical contribution, as done by others in the literature.

Also, we extend the reasoning to any accelerated charged or colored particle, non-massless. We are certain many didn't connect the dots on this before. Beyond curiosities, we discovered implications for the decay of accelerated particles especially proton decay, which is now possible, without New Physics, when a proton is sufficiently accelerated, the reason being that it is an interaction/Unruh radiation effect, not a decay, even if it might appears so. This does not change our conclusions about the absence of inertial proton decay, and as a result the improbability that supersymmetry, superstrings, and most popular GUTs and TOEs be physical.

Doing so we saw that photon emission when electron jump down in energy level from an excited state can also be seen as a Larmor radiation. It is a new point of view on electron (smooth) leaps.

We linked the Unruh effect to the ambiguity of the number of particles seen by different observers in curved spacetime, and noted also the link to particle creations in the presence of gravitation wave or perturbations. Armed with this, we explained all the contributions to the Hawking radiation of black holes, following the same reasoning. Doing so we also showed how, and why, there are multiple ways to obtain the result.

We have also shown that accelerated masses gravitationally radiate in conventional and multifold universes, and simple arguments for memory effects associated to all interactions: gravity, WED, QCD, weak/electroweak, even when they are very small effects. For gravity, these effects can only be hoped to be detected in near future for collisions between major cosmic bodies, like black hole mergers or maybe some black holes binaries, as part of gravitational wave programs.

Finally, while everything discussed here is valid for conventional universes, we also discussed how multi-fold universes can provide additional microscopic explanation for the Unruh effect, and justifies different excitation of (different) vacuum, in the presence of gravity or entanglement, if spacetime is modeled by random walks of massless Higgs bosons.

In passing, we also reaffirmed and explained that gravity and entanglement break the Reeh-Schielder theorem, despite theorems in the literature that indicate that in a continuous GR curved spacetime, it might still hold.

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