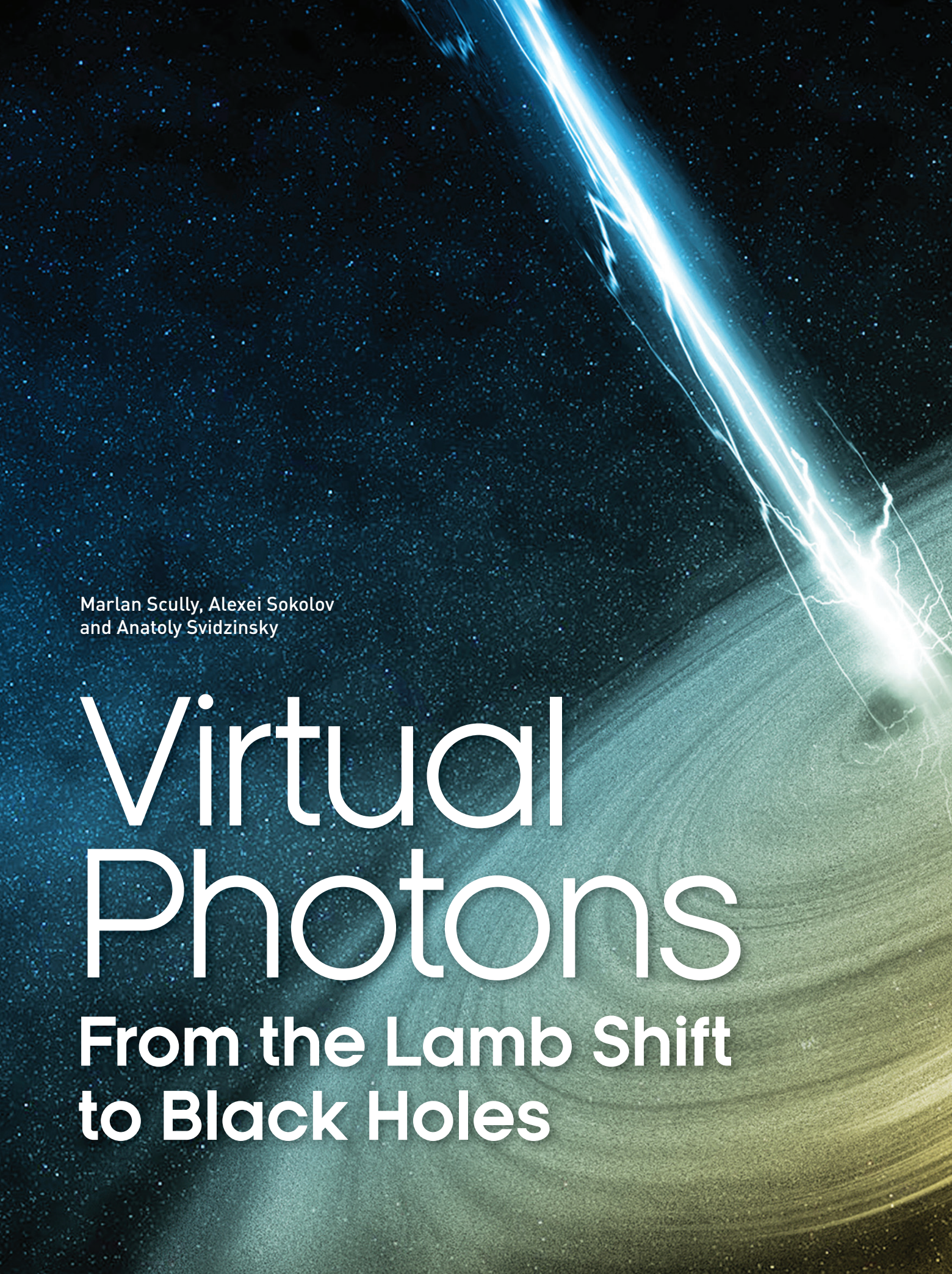

Marlan Scully, Alexei Sokolov
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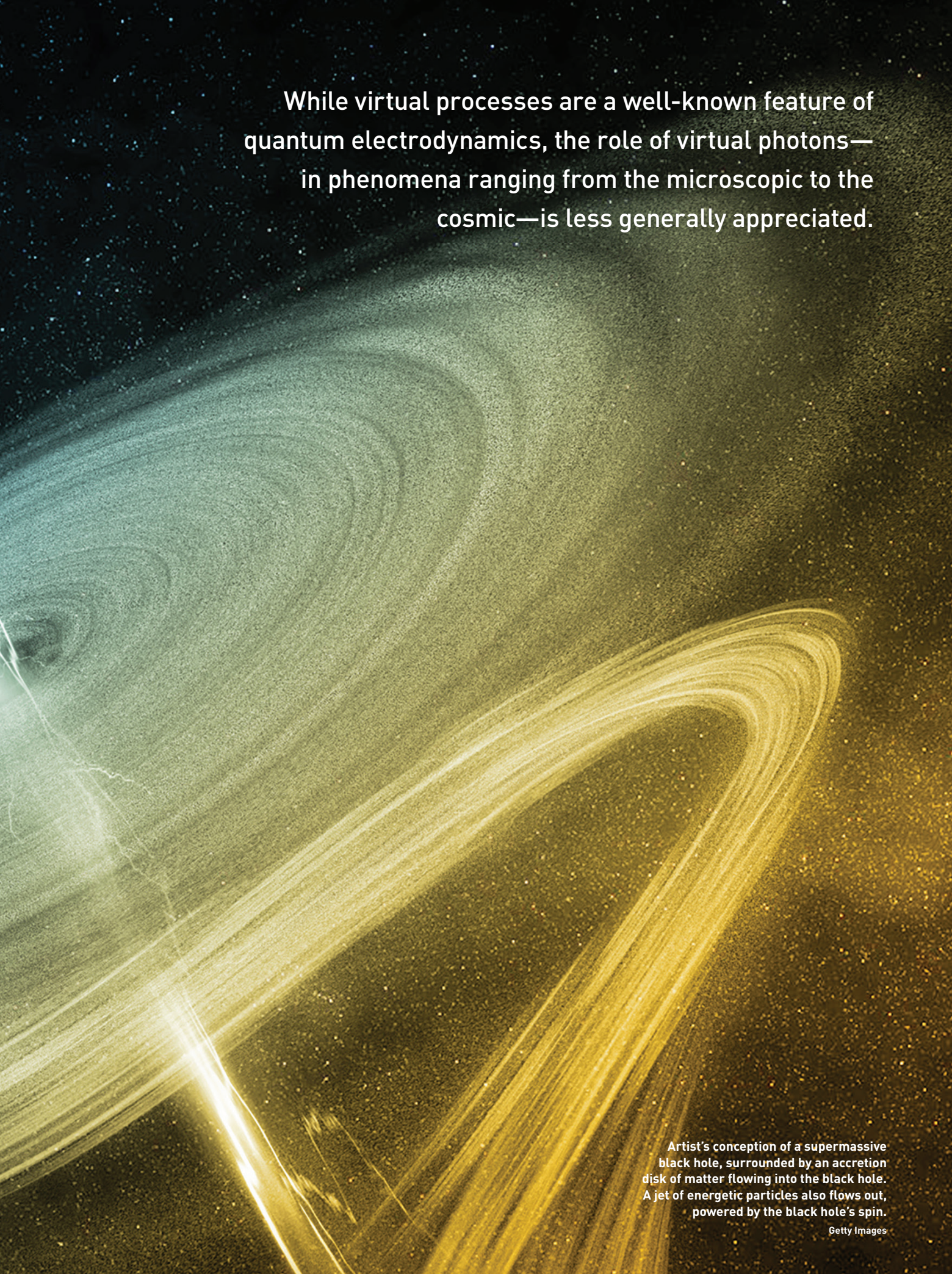
Virtual Photons

From the Lamb Shift to Black Holes

While virtual processes are a well-known feature of quantum electrodynamics, the role of virtual photons—in phenomena ranging from the microscopic to the cosmic—is less generally appreciated.



Artist's conception of a supermassive black hole, surrounded by an accretion disk of matter flowing into the black hole. A jet of energetic particles also flows out, powered by the black hole's spin.

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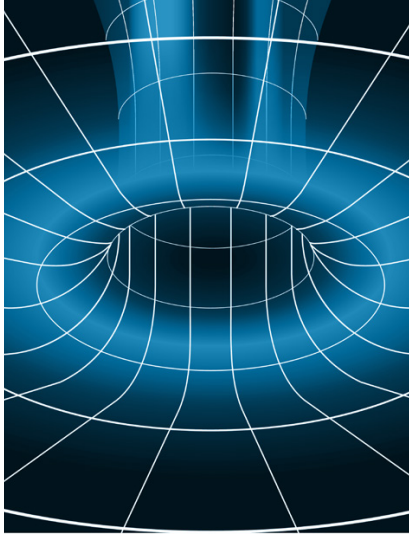


Many processes in quantum field theory occur via virtual particles. These short-lived "imposters" of real particles—a transient feature of processes such as Thompson scattering—do not conserve energy and are thus said to be "off energy shell." Virtual particles get away with having the "wrong" energy because of the time-energy uncertainty principle inherent in quantum mechanics.

It's also possible to have virtual photons, as a result of virtual atomic transitions in which energy is not conserved on a short time scale. For example, an electron in an atom can jump to an excited state, giving rise to a virtual photon that is quickly reabsorbed when the electron jumps back to the ground state. These virtual processes, which seem surreal, can have real effects. They can, for example, shift the energy levels of atoms; indeed, the measurement of these shifts in the hydrogen atom in 1947 garnered Willis Lamb the Nobel Prize in Physics, and provided a stimulus for the development of renormalizable quantum electrodynamics (QED).

But the virtual photon has other surprises up its sleeve. It plays a role, for instance, in the microscopic Raman effect, a nonlinear optical process of considerable practical importance. And recent work by our group suggests that the conversion of virtual photons into directly observable real photons in the curved spacetime of black holes could, through the Unruh radiation emitted by accelerating atoms, link up in an interesting way with the celebrated Hawking radiation emanating from these exotic cosmic phenomena.

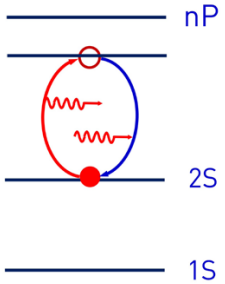
In this feature, we lay out some of the connections between these micro and very macro phenomena—starting with a look at what makes a process "virtual."

Virtual processes lie at the heart of QED. One example is the QED picture of Thomson scattering.

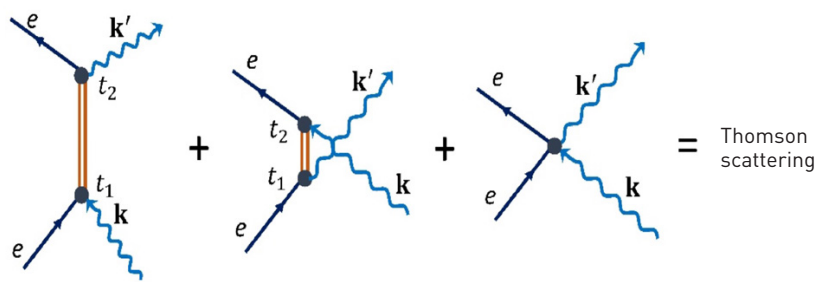
Virtual processes

Virtual processes lie at the heart of QED. One example is the QED picture of Thomson scattering—the low-energy limit of Compton scattering, in which an incident photon is scattered by a slow free electron.

The three Feynman diagrams below provide three different pictures of Thomson scattering. In left-hand diagram, the absorption of a photon at time t_1 is followed by an emission of a photon of the same energy at t_2, with the system in a virtual state between t_1 and t_2. The center diagram shows an "emission-first" scenario, in which the system enters a virtual state and emits a photon at t_1, with absorption of a second photon at t_2 returning the system to the original state. The



Virtual photons, as seen in the Lamb shift. An atom's 2S state is shifted when an electron jumps to a higher n state and emits a virtual photon; the atom then quickly reabsorbs this virtual photon and returns to the 2S state.



Feynman diagrams for Thomson scattering, for the absorption-first case (absorption, followed after a time delay by emission), the emission-first case (photon emission, followed by absorption), and instantaneous absorption and emission. In the first two cases, the system is in a virtual state between times t_1 and t_2.

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diagram at right shows instantaneous emission and absorption, with no virtual state. Both the absorption-first and emission-first events conserve momentum, but not energy—or, more precisely, energy is conserved overall, but not when the system is in an intermediate, virtual state between t_1 and t_2.

Mathematically, two expressions govern these interactions between light and electrons: $e\mathbf{p}\cdot\mathbf{A}$ and $e^2\mathbf{A}^2$, where e is the electron charge, $\mathbf{p}$ is the electron momentum, and $\mathbf{A}$ is the vector potential. The $e\mathbf{p}\cdot\mathbf{A}$ interaction occurs twice in both the absorption-first and emission-first scenarios for electron scattering. (Interestingly, the magnitudes of the scattering amplitudes from the left and middle diagrams are identical but opposite in sign—that is, they cancel.) In contrast, the instantaneous case uses the $e^2\mathbf{A}^2$ term only once, and only that term contributes to Thomson scattering.

Acceleration radiation

Beyond Thomson scattering, other phenomena, such as the Raman effect, also involve virtual states (see sidebar, right). But how do these micro phenomena relate to the macro physics of black holes? The answer arises through a consideration of Unruh radiation—the radiation that quantum field theory predicts for accelerating atoms, and that, we argue, can be understood as the result of virtual photons becoming real ones.

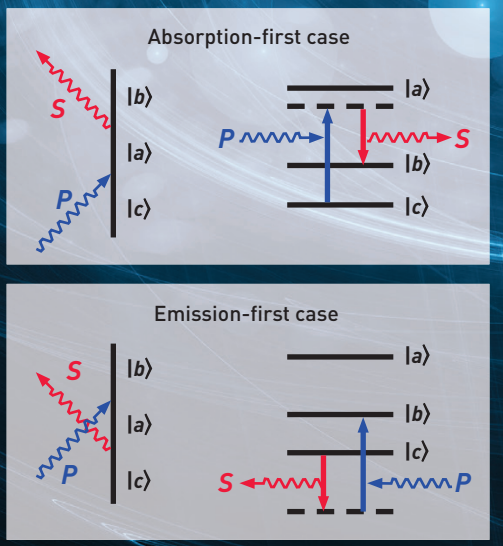
One of the most intriguing results of modern quantum field theory is that ground-state atoms, accelerated through vacuum, are promoted to an excited state just as if they were in contact with a blackbody thermal field. This process is accompanied by the emission of a photon that propagates to infinity. The probability of excitation of a uniformly accelerated atom, at frequency ω, with the simultaneous emission of a photon is proportional to the Planck factor—that is, $P \propto (e^{\hbar\omega/k_B T_U} - 1)^{-1}$. T_U in this expression is the effective, or Unruh, temperature, given by $T_U = \hbar a/2\pi c k_B$, where a is the atom acceleration and k_B is the Boltzmann constant.

What this means is that, for an accelerating observer (or atom), the background will appear, in the acceleration reference frame, to be in thermodynamic equilibrium, with temperature T_U; in steady state the atom populations are given by the Boltzmann distribution with T_U. This is known as the Fulling–Davies–Unruh effect.

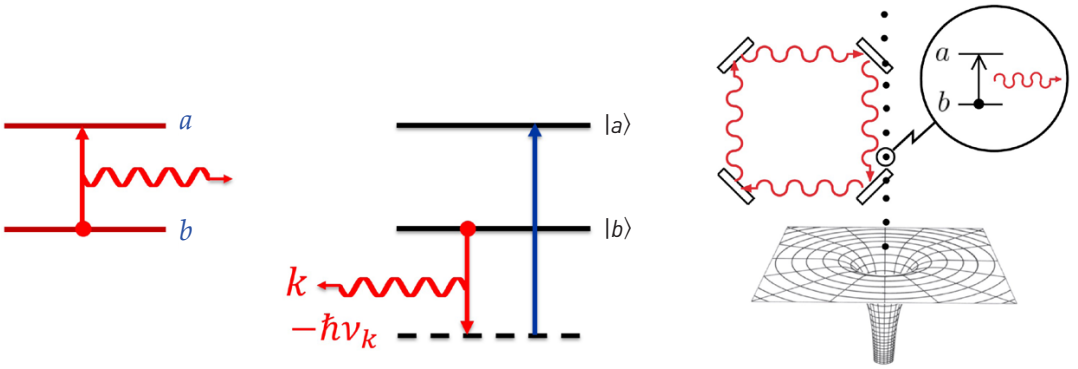
To understand this acceleration radiation, we suggest that a virtual process is at work. In this process, the accelerating atom jumps from the ground state to

Virtual photons and the Raman effect

Like the Lamb shift and Thomson scattering, the Raman effect provides an example of a process in which virtual photons play a role. Ordinary Raman scattering proceeds along two kinds of pathways—one ("absorption first") in which the higher-frequency pump photon is absorbed, followed by emission of a lower-frequency Stokes (signal) photon; and the other ("emission first") involving the excitation of the molecule into a virtual state and at the same time emitting a Stokes photon, followed by absorption of a pump photon. (Mathematically, the latter case is due to counter-rotating terms in the Hamiltonian—much as with the acceleration radiation discussed in the main text.)



Raman scattering Feynman diagrams (left) and energy-level diagrams (right)



Acceleration radiation: When virtual photons become real

(Left) The counter-resonant virtual processes in which an atom is excited as it simultaneously emits a photon. (Center) In acceleration radiation of a two-level atom, the atom is promoted from $|b\rangle$ to $|a\rangle$ by emitting a virtual photon, which becomes real when the atom accelerates away. A change in the center-of-mass motion energy allows energy to be conserved. (Right) In a thought experiment, atoms in the ground state $|b\rangle$ are accelerated through small holes in the corner reflectors of a microwave or optical cavity by (for example) a strong gravitational field. Such cavity effects can increase the otherwise extremely small probability that virtual photons might be converted into real ones.

an excited state, leading to the emission of a virtual photon. Generally, the virtual photon would be quickly reabsorbed, maintaining the overall energy conservation. However, if the atom accelerates away from the original point of virtual emission, there is a small probability that the virtual photon will "get away" before it is reabsorbed.

Thus, for acceleration radiation, two conditions—the atom's acceleration, and the system's nonadiabaticity—combine to produce the emitted light. Those conditions, by breaking and interrupting virtual processes, allow the virtual photons to be rendered real. The conversion happens at the expense of the energy supplied by the external force field driving the center-of-mass motion of the atom against the radiation reaction force. (The notion that virtual photons can become real ones, while seemingly exotic, is not entirely new, and has been suggested as an explanation for, among other things, the dynamic Casimir effect.)

Boosting the odds

Photon emission by an accelerating atom in free space, while possible, is extremely improbable in realistic laboratory conditions—that is, when the atomic frequency ω is significantly greater than a/c (the atom acceleration divided by the speed of light). Even for large acceleration frequency ($a/c = 10^8$ Hz), and microwave frequencies ($\omega = 10^{10}$ Hz), the probability of generating an Unruh photon is approximately one in 10^{200}. As a result, acceleration radiation has not yet been observed experimentally.

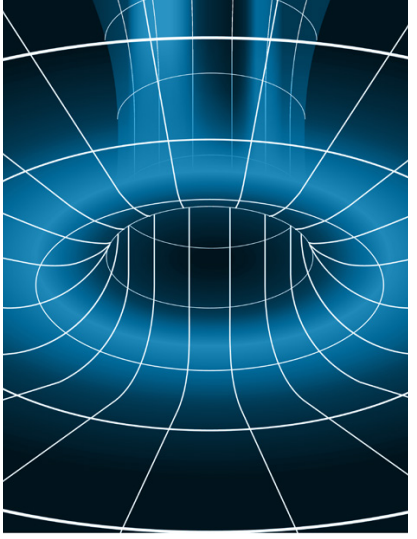
One way of boosting the odds of photon emission could be to leverage cavity QED, by turning on coupling between field and the atom very quickly. This can be achieved when atoms are accelerated through a high-Q cavity, which produces a strong nonadiabatic effect at the cavity boundaries. Under that scenario, the probability that a ground-state atom might be excited to its upper level, assuming the parameters above, is around 10^{-3}—many orders of magnitude larger than the free-space case, no longer vanishingly small, and potentially observable.

The enhanced rate of emission into the cavity mode comes from the nonadiabatic transition at the cavity boundaries; the standard Unruh excitation comes from the nonadiabatic transition in free space due to the time dependence of the Doppler-shifted field frequency as seen by the accelerating atom.

Black holes and Hawking radiation

With this background, we are ready to tackle how virtual photons can become real photons in the dramatically curved spacetime of a black hole. We begin with a quick but necessary detour to review black holes, the problem of their entropy, and Stephen Hawking's solution to that problem.

The existence of black holes—objects from which nothing can escape—is one of the most striking, best-known predictions of general relativity. A black hole is defined as a singularity in spacetime, surrounded by an "event horizon"—a sort of one-way membrane



that allows matter and light in, but does not allow them out. The gravitational radius of a black hole, or Schwarzschild radius (the distance at which the escape velocity equals the speed of light) is given by the expression $r_g = 2MG/c^2$, where M is the objects mass and G is the gravitational constant.

Interestingly, the possibility that "the attractive force of a heavenly body could be so large, that light could not flow out of it" was proposed by Peter Laplace in a 1798 paper. But it requires a full theory of gravity, Einstein's general relativity, to understand the behavior of matter in such a body's strong gravitational fields. More specifically, the prevailing view (memorably described by John Wheeler as the "no-hair" theorem) holds that black holes are extremely simple objects characterized by only three physical properties: mass, charge and angular momentum.

The existence of black holes is one of the best-known predictions of general relativity

That very simplicity, however, raises a problem, as it suggests that black holes are entropy sinks—that is, that whereas the matter falling into a black hole has enormous number of possible thermodynamic microstates, after the matter falls into the black hole it is uniquely determined by only three variables. That implies a breakdown of the second law of thermodynamics, which holds that the entropy of a closed system cannot decrease.

The work of Jakob Bekenstein and Stephen Hawking offered a resolution to the dilemma: they showed that black holes possess an entropy proportional to the surface area of the event horizon—that is, to $4\pi r_g^2$. Hence, if a black hole's mass increases, its surface area and entropy also grow. Hawking further showed, in the framework of quantum field theory in curved spacetime, that quantum effects yield emission of blackbody radiation by black holes at the expense of their mass—the celebrated "Hawking radiation."

Heuristically, Hawking described the radiation in terms of the quantum tunneling of virtual particles across the event horizon. He showed that this radiation, tunneling from inside a spherical Schwarzschild black hole to the "outside world" is described by a thermal field with temperature $T_{BH} = \hbar c^3/8\pi GMk_B$. Hawking's analysis treats gravity as classical and the radiation field as quantized. The radiation arises from placing a quantum field in curved spacetime.

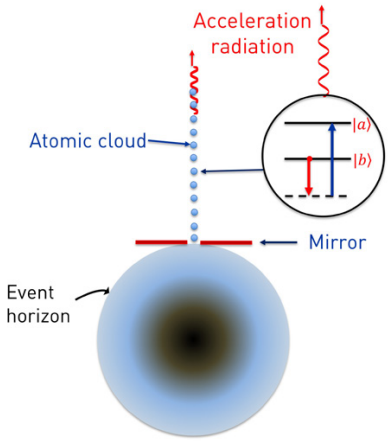
The physical source of Hawking radiation can be interpreted in multiple ways. It can be viewed as particle–antiparticle radiation emitted from just beyond the event horizon, as a result of virtual particles being "boosted" by the black hole's spatial curvature into becoming real particles. In another view, vacuum fluctuations cause a particle–antiparticle pair to appear close to the black hole's event horizon, with one member falling into the black hole and the other escaping. In still another interpretation, Hawking radiation is a quantum-tunneling effect, whereby particle–antiparticle pairs are created from the vacuum, and one tunnels outside the event horizon.

When the spectrum of such particles is calculated, one finds a thermal spectrum with Hawking temperature, T_{BH}. The Hawking temperature also provides a way to calculate the black hole entropy, S, using the thermodynamic relation $dS = d(Mc^2)/T_{BH}$. The resulting final expression— $S = (k_B c^3/4\hbar G)A$ —directly relates the entropy to the black hole's surface area, A. Hawking radiation thus provides a mechanism for the black hole to radiate energy and entropy, completing the thermodynamic connection.

T_{BH}, T_U, and acceleration radiation near a black hole

We can now make the link between the Unruh radiation of an accelerating atom—which, we've suggested, arises from virtual photons becoming real—and the Hawking radiation that manages entropy at the event horizon of a black hole.

Let's assume that the acceleration of a falling particle equals the gravitational acceleration at the event horizon, $a = GM/r_g^2$, where r_g is the Schwarzschild radius, $r_g = 2MG/c^2$. It turns out, in substituting these relations, that the expression for the Unruh temperature of



Model of a black hole bombarded by a pencil-like cloud of two-level atoms falling radially from infinity. The relative acceleration between the atoms and the field generates acceleration radiation that, to a distant observer, would look identical to the Hawking radiation tied to the black hole's intrinsic entropy.

radiation from an accelerating atom, T_U, is identical to the expression for the Hawking temperature of radiation from a black hole, T_{BH}. (A more rigorous treatment of the mathematics can be found at https://arxiv.org/abs/1709.00481v2.)

Thus, as atoms accelerate toward a black hole, emitted photons of their acceleration radiation are characterized by the Hawking temperature. Furthermore, although the equivalence principle tells us that an atom falling in a gravitational field does not "feel" the effect of gravity (that is, in special-relativity terms, its 4-acceleration equals zero), there is *relative* acceleration between the atoms and the field modes.

This leads to the generation of acceleration radiation that, to a distant observer, would *look* like Hawking black-hole radiation with temperature T_{BH}; the emitted acceleration radiation is essentially thermal, and has an entropy analogous to the black-hole entropy derived from the Hawking temperature. Yet the physics of the two processes are different: the acceleration radiation arises from virtual photons due to atoms cascading into the black hole, whereas the Hawking radiation requires no extra matter, and arises entirely from the black-hole geometry.

Rich physics

We hope that this brief glimpse suggests the rich physics embedded in the study of virtual photons, spanning intellectual horizons from the micro-scale of the Lamb shift and the Raman and Casimir effects to the macro-scale of the Unruh and Hawking radiations. To end this review, we want to stress that virtual photons are not simply of theoretical interest, but have relevance to applied topics such as quantum informatics and quantum thermodynamics. Indeed, studying noise-induced coherence effects in the operation of quantum heat engines was what initially got us interested in exploring a virtual-photon approach to the Unruh effect—and, through that, to the radiation expected from accelerating atoms near a black hole.

Further, in a 2010 article in *Science* (titled "The Lamb shift—Yesterday, today, and tomorrow"), we made the point that large ensembles of entangled atoms (such as those considered by R.H. Dicke in the mid-1950s) could decohere due to the many-atom Lamb-shift virtual-photon effects. However, symmetry of the atomic distribution can protect states from being altered by virtual photons. This is important for developing systems with robust quantum memory, long storage time and fast readout.

The take-home message for young optical scientists: viewing advanced quantum mechanics and quantum field theory from the perspective of modern quantum optics can offer some surprising insights, at many scales. OPN

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- An expanded list of references and resources can be found online at www.osa-opn.org/virtual-photons.