

# Expansion, Redshift, and Lost Visibility: The Gravitational and Thermodynamic Fate of Light in an Expanding Universe

## 1. Introduction: The Phenomenon of Cosmic Dilution and the Fate of Light

The observation that the universe is undergoing metric expansion stands as one of the most profound and philosophically disruptive discoveries of modern cosmology, fundamentally altering humanity's understanding of space, time, causality, and the ultimate fate of the cosmos. Initially formulated through the theoretical frameworks of Alexander Friedmann and Georges Lemaître, and observationally confirmed by Edwin Hubble's meticulous analysis of galactic recession velocities in the 1920s, the expanding universe paradigm asserts that the fabric of spacetime itself is continuously stretching.<sup>1</sup> This expansion does not merely drive massive galaxies apart; it exerts a profound, measurable, and inescapable influence on everything traversing the cosmic void, most notably electromagnetic radiation.

As light propagates through the expanding spacetime of the universe, it undergoes a phenomenon known as cosmological redshift.<sup>4</sup> Unlike classical kinematic effects, the wavelength of the light stretches in perfect tandem with the metric expansion of the universe itself, leading to a proportional decrease in its frequency and, consequently, a precipitous drop in its energy.<sup>5</sup> From the perspective of a local observer—such as an astronomer on Earth—this light arrives significantly weaker, colder, and temporally dilated.<sup>7</sup> In universes dominated by dark

energy, such as the widely accepted  $\Lambda$  CDM (Lambda Cold Dark Matter) model of our own universe, this expansion is not merely constant but accelerating.<sup>9</sup> This acceleration leads to the inevitable formulation of cosmic event horizons.<sup>9</sup> In extreme cosmological cases, light emitted today from beyond a certain proper distance may never reach a distant observer at all.<sup>2</sup> This

happens not because the light ceases its local propagation at the universal speed limit  $c$ , but because the intervening space expands at a rate that outpaces the light's ability to traverse it.<sup>11</sup>

This phenomenon invites a fundamental ontological and physical inquiry, echoing the precise questions posed by ArcSecs: What ultimately happens to all of that redshifted and seemingly "lost" light? Does the energy of redshifted photons simply vanish, violating the foundational laws of thermodynamics and energy conservation that govern classical physics? Furthermore, does light that falls beyond our cosmological event horizon become entirely irrelevant to our physical reality because we can no longer see it, or does it remain an active, integral participant in the gravitational and thermodynamic accounting of the universe?

To answer these questions requires an exhaustive analysis of the mechanics of cosmological redshift, the nuanced status of energy conservation within the framework of Albert Einstein's general relativity, the precise taxonomy of cosmic horizons, and the ultimate thermodynamic

and gravitational fate of light in an expanding universe. By dissecting the intricacies of the Friedmann–Lemaître–Robertson–Walker (FLRW) metric, the local conservation of the stress-energy tensor, the lack of global time-translation symmetry, and the quantum thermodynamics of de Sitter space, this report will demonstrate that while light may indeed be lost to optical visibility, it is never lost to the rigorous mathematical, gravitational, and thermodynamic accounting of the spacetime continuum.

## 2. The Architecture of Expanding Spacetime and Cosmological Redshift

To comprehend the fate of light in the cosmos, one must first establish the precise geometric framework through which it travels. In the theory of general relativity, the universe on its largest observable scales is modeled assuming the Cosmological Principle, a foundational axiom which posits that the universe is both spatially homogeneous and isotropic.<sup>1</sup> Homogeneity dictates that the universe looks the same at every location, while isotropy dictates that it looks the same in every direction.<sup>1</sup> The unique exact solution to Einstein's field equations that satisfies these dual macroscopic symmetries is the Friedmann–Lemaître–Robertson–Walker (FLRW) metric.<sup>1</sup>

### 2.1 The FLRW Metric and the Scale Factor

The FLRW metric describes a highly symmetric, dynamic spacetime where the spatial slice at any given cosmic time is multiplied by a time-dependent scale factor, denoted as  $a(t)$ . In spherical comoving coordinates  $(r, \theta, \phi)$  and proper cosmological time  $t$ , the invariant spacetime interval  $ds^2$  is written mathematically as:

$$ds^2 = -c^2 dt^2 + a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right)$$

Here,  $c$  is the speed of light in a vacuum, and  $k$  represents the spatial curvature constant, which can take values of  $+1, 0, \text{ or } -1$  for closed, flat, and open geometric topologies, respectively.<sup>1</sup> The scale factor  $a(t)$  is the crucial dynamic element; it dictates the physical, proper distance between any two comoving observers (such as two distant galaxy clusters) over time.<sup>6</sup> When  $a(t)$  increases, the universe is expanding; when it decreases, the universe is contracting.

### 2.2 The Mechanics of Cosmological Redshift

When a photon is emitted by a distant celestial source and travels toward Earth, it propagates

along a null geodesic, a path through spacetime where the invariant interval  $ds^2 = 0$ .<sup>6</sup> Because the universe is undergoing active metric expansion while the photon is in transit, the physical distance between the crests of the electromagnetic wave stretches exactly in proportion to the scale factor  $a(t)$ .<sup>4</sup>

If a photon is emitted at an earlier time  $t_e$  with an initial wavelength  $\lambda_e$  and observed at a later time  $t_o$  with a observed wavelength  $\lambda_o$ , the relationship between the wavelengths is governed entirely by the ratio of the scale factors at those respective times:

$$\frac{\lambda_o}{\lambda_e} = \frac{a(t_o)}{a(t_e)} = 1 + z$$

This elegant relationship serves as the formal definition of the cosmological redshift, denoted by  $z$ .<sup>6</sup> It is critical to distinguish cosmological redshift from the Special Relativistic Doppler shift, a confusion that pervades much of the popular and even undergraduate literature.<sup>3</sup> A standard Doppler shift occurs due to the relative kinetic motion of objects through a static, pre-existing space—much like a police siren changing pitch as it drives past an observer.<sup>4</sup> In the Special Relativistic Doppler effect, the wavelength of the emitted radiation depends solely on the relative velocity of the object at the exact instant the photons are emitted.<sup>4</sup> Cosmological redshift, however, is fundamentally different. It is the result of the expansion of space itself over the entire duration of the photon's journey.<sup>4</sup> The distant emitting galaxy is not necessarily moving through its local space at high relativistic speeds; rather, the space between the galaxy and the observer is dilating, stretching the photon en route.<sup>3</sup> Therefore, the wavelength at which the radiation is originally emitted is continuously lengthened as it travels through expanding space.<sup>4</sup> This stretching effect not only alters the wavelength but also dilates the arrival time of the wave packets, meaning that events observed at high redshift appear to unfold in slow motion—a phenomenon known as cosmological time dilation.<sup>7</sup>

### 3. The Chimera of Global Energy Conservation in General Relativity

Because the energy of a photon is inversely proportional to its wavelength (governed by the Planck-Einstein relation  $E = hc/\lambda$ , where  $h$  is Planck's constant), an increase in wavelength directly and unavoidably results in a decrease in the photon's energy.<sup>5</sup> If the universe is filled with a cosmic microwave background (CMB) consisting of countless photons all losing energy simultaneously as the universe expands, one is forced to confront a glaring paradox: Where does all that energy go? Does cosmological redshift inherently violate the foundational law of conservation of energy?

The rigorous, albeit counterintuitive, answer provided by modern theoretical physics is that energy is simply not conserved on a global scale in an expanding universe.<sup>19</sup> The notion that "energy can neither be created nor destroyed" is a cornerstone of classical mechanics and thermodynamics, but it requires specific geometric preconditions that the universe as a whole does not meet.

### 3.1 Noether's Theorem and the Loss of Time-Translation Symmetry

To understand exactly why global energy conservation fails in cosmology, one must consult Noether's Theorem. Formulated by the brilliant mathematician Emmy Noether in 1915, the theorem states that every continuous, differentiable symmetry of the action of a physical system has a corresponding, mathematically rigorous conservation law.<sup>22</sup> For instance, if a physical system is symmetric under spatial translation (the laws of physics are the same here as they are a mile away), it yields the conservation of momentum. If a system exhibits rotational symmetry (the laws of physics do not change depending on which direction you face), it yields the conservation of angular momentum.

Crucially, the law of conservation of energy is the direct mathematical consequence of time-translation invariance (or time-translation symmetry).<sup>7</sup> If the background environment and the dynamical rules governing a system do not change over time, the total energy of that system remains absolutely constant.<sup>20</sup> In classical Newtonian mechanics and Einstein's special relativity, spacetime is treated as a static, unchanging stage; thus, time-translation symmetry holds perfectly, and energy is strictly conserved.<sup>20</sup>

However, general relativity posits that spacetime is not a static stage, but a dynamic, malleable entity that responds to mass and energy.<sup>20</sup> In an expanding universe governed by the FLRW metric, the spatial geometry is constantly changing as a function of time due to the evolving scale factor  $a(t)$ .<sup>15</sup> Because the metric of the universe today is physically and geometrically different from the metric of the universe yesterday, the background environment is not fixed. Consequently, the universe lacks time-translation symmetry.<sup>15</sup>

In the highly formalized language of differential geometry, a spacetime possesses time-translation symmetry if—and only if—it admits a timelike Killing vector field. A Killing

vector field  $\xi^\mu$  (named after Wilhelm Killing) satisfies the Killing equation:

$$\nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu = 0$$

If a timelike Killing vector exists in a given spacetime, one can define a globally conserved energy by contracting the stress-energy tensor with this vector.<sup>7</sup> Because the FLRW spacetime describes an expanding, non-static cosmos, no such globally defined timelike Killing vector field exists.<sup>26</sup> Therefore, by the rigorous mathematical definitions of Noether's Theorem and general relativity, global energy is not a conserved quantity.<sup>20</sup>

## 3.2 The Gravitational Potential Energy Debate and Pseudotensors

It is occasionally argued in undergraduate pedagogical settings that the energy lost by photons due to cosmological redshift is not truly lost, but is instead seamlessly transferred into the gravitational field.<sup>4</sup> In this view, the expanding universe performs "work," or the lost positive energy of the photons is converted into negative gravitational potential energy.<sup>4</sup> From this perspective, the sum of the positive energy of matter and radiation and the negative energy of the gravitational field remains a constant zero, thereby "rescuing" the first law of thermodynamics.<sup>4</sup>

While this conceptualization provides psychological comfort to those seeking to preserve the sanctity of energy conservation, many leading theoretical physicists and cosmologists, including Sean Carroll, argue that this perspective is fundamentally flawed, mathematically ambiguous, and pedagogically misleading.<sup>20</sup> In general relativity, the "energy of the gravitational field" cannot be localized. Because of the Equivalence Principle, one can always choose a local reference frame (a freely falling coordinate system) where spacetime is locally flat and the gravitational field entirely vanishes.<sup>20</sup> Consequently, there is no uniquely defined local density of gravitational energy.<sup>20</sup> Mathematically, this is represented by the fact that one cannot construct a true tensor out of the first derivatives of the metric (the Christoffel symbols).<sup>20</sup>

Historically, physicists have attempted to quantify gravitational energy using mathematical constructs known as pseudo-tensors (such as the Landau-Lifshitz pseudotensor).<sup>23</sup> However, pseudotensors are coordinate-dependent and lack the objective, coordinate-free reality of true tensors.<sup>23</sup> Carroll asserts that explaining energy loss as being "canceled by negative gravitational energy" merely quiets questioning minds rather than increasing true physical understanding.<sup>20</sup> The more accurate and physically insightful explanation is that spacetime acts as an active participant in dynamics. It can independently give energy to, or absorb energy from, matter and radiation.<sup>20</sup> When a photon propagates through expanding space, the dynamic spacetime acts upon it, and the total energy of the photons simply decreases.<sup>5</sup> A decrease in energy due to expansion is just as much a "violation" of classical energy conservation as an increase in energy would be.<sup>20</sup>

## 3.3 Conformal Symmetry: A Localized Exception for Light

There is a subtle mathematical caveat to the lack of Killing vectors in cosmology that specifically applies to light. While the expanding universe lacks a true timelike Killing vector, it does possess a *conformal* timelike Killing vector when expressed in conformal time,  $\tau$ .<sup>26</sup> A conformal Killing vector  $K^\mu$  satisfies a modified version of the Killing equation:

$$\nabla_\mu K_\nu + \nabla_\nu K_\mu = \phi g_{\mu\nu}$$

where  $\phi$  is a scalar function and  $g_{\mu\nu}$  is the metric tensor.<sup>26</sup> This property yields a specialized, narrow conservation law for systems that possess a traceless stress-energy tensor ( $g_{\mu\nu}T^{\mu\nu} = 0$ ), such as the electromagnetic field (radiation).<sup>26</sup>

When analyzed purely in conformal time, the energy of the electromagnetic field is mathematically conserved.<sup>26</sup> However, this conformal energy cannot be meaningfully added to the standard energy associated with massive particles (which do not have a traceless stress-energy tensor), rendering a unified, global conservation law that encompasses both matter and radiation impossible.<sup>26</sup> While conformal symmetry is mathematically elegant, it does not resurrect the classical notion of global energy conservation in the physical universe.<sup>26</sup>

## 4. Local Cosmic Accounting: The Stress-Energy Tensor

If global energy is not conserved, does this imply that physics in an expanding universe is entirely chaotic and unpredictable? Absolutely not. General relativity enforces a strict, unbreakable *local* conservation of energy and momentum, governed by the vanishing covariant divergence of the stress-energy tensor.<sup>4</sup>

The Einstein Field Equations dictate that the geometry of spacetime (represented by the Einstein tensor  $G_{\mu\nu}$ ) is intimately coupled to the matter and energy content of spacetime (represented by the Stress-Energy tensor  $T_{\mu\nu}$ ):

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The Bianchi identities mandate that the covariant derivative of the Einstein tensor is identically zero ( $\nabla_{\mu}G^{\mu\nu} = 0$ ). Therefore, to maintain mathematical consistency, the covariant derivative of the stress-energy tensor must also be zero<sup>36</sup>:

$$\nabla_{\mu}T^{\mu\nu} = 0$$

This equation represents the local conservation law for energy and momentum in general relativity.<sup>20</sup> It is vital to note the presence of the covariant derivative ( $\nabla_{\mu}$ ), which is not a simple partial derivative. The covariant derivative includes connection coefficients (Christoffel symbols) that explicitly account for the curvature and expansion of spacetime.<sup>36</sup> Thus, the equation does not state that total energy is a static, constant number; rather, it states that energy evolves in a highly precise, deterministic manner dictated by the local geometry.<sup>20</sup>

## 4.1 Fluid Equations of State and Density Scaling

To understand the fate of light and matter, cosmologists model the large-scale contents of the universe as a perfect fluid, with the stress-energy tensor defined by its energy density  $\rho$  and its pressure  $P$ :

$$T^{\mu\nu} = \left( \rho + \frac{P}{c^2} \right) U^\mu U^\nu + P g^{\mu\nu}$$

Where  $U^\mu$  is the 4-velocity of the fluid.<sup>1</sup> Expanding the local conservation equation  $\nabla_\mu T^{\mu\nu} = 0$  within the context of the FLRW metric yields the cosmological continuity equation:

$$\dot{\rho} + 3 \frac{\dot{a}}{a} \left( \rho + \frac{P}{c^2} \right) = 0$$

The relationship between pressure and density for any given component of the universe is defined by its equation of state parameter,  $w = P/(\rho c^2)$ .<sup>6</sup> The ultimate fate of any

cosmological component depends entirely on its value of  $w$ .

To illustrate how different components of the universe react to expansion, consider the following structured data regarding equations of state:

| Cosmological Component         | Equation of State ( $w$ ) | Density Scaling with Scale Factor ( $a$ ) | Physical Explanation and Implication   |
|--------------------------------|---------------------------|---|--|
| Non-relativistic Matter (Dust) | $w = 0$                   | $\rho_M \propto a^{-3}$                   | Matter exerts negligible pressure. Its density drops purely due to the geometric increase in volume ( $V \propto a^3$ ) as space expands. Total mass remains |

|  |           |  |  |
|--|-----------|--|--|
|  |           |  | constant.  |
| <b>Radiation<br/>(Photons/CMB)</b>             | $w = 1/3$ | $\rho_R \propto a^{-4}$                  | Radiation exerts radiation pressure. Density drops due to volume expansion ( $a^{-3}$ ) multiplied by the cosmological redshift of individual photons ( $a^{-1}$ ).    |
| <b>Dark Energy<br/>(Cosmological Constant)</b> | $w = -1$  | $\rho_\Lambda \propto a^0$<br>(Constant) | Vacuum energy exerts negative pressure. Its density remains absolutely constant even as space expands. Therefore, the total energy of dark energy increases over time. |

This structured accounting proves that while photons lose energy as individuals, they do not violate local physics. Their energy scaling as  $a^{-4}$  is perfectly predicted and accounted for by the general relativistic continuity equation.<sup>6</sup> As the universe expands, radiation rapidly dilutes compared to matter, causing the universe to transition historically from a radiation-dominated era (shortly after the Big Bang) to a matter-dominated era, and finally to the dark energy-dominated era we observe today.<sup>16</sup>

Therefore, to answer the first part of ArcSecs' inquiry: What happens to all that light? The light simply dilutes and redshifts in exact accordance with the fluid equations of general relativity. The energy does not disappear into a mysterious void; it smoothly transitions out of existence as dictated by the dynamically evolving background of spacetime.

### 5. The Taxonomy and Mechanics of Cosmic Horizons

As ArcSecs astutely observes in the prompt, light from beyond certain "cosmic horizons" may never reach us because the distance grows too quickly. To rigorously address what happens to

light beyond these horizons, one must first resolve a pervasive issue in cosmological literature, aptly termed "Expanding Confusion" by astrophysicists Tamara Davis and Charles Lineweaver.<sup>2</sup> Davis and Lineweaver demonstrated that fundamental misconceptions regarding superluminal expansion and cosmic horizons are widespread even among professional physicists.<sup>2</sup> There are three distinct, mathematically defined horizons in cosmology that dictate what we currently see, what we could ever theoretically see, and the absolute limits of causality.

## 5.1 The Hubble Sphere and Superluminal Recession

The Hubble Sphere is defined as the exact distance at which the recession velocity of galaxies due to cosmic expansion equals the speed of light,  $v = c$ .<sup>3</sup> According to Hubble's Law ( $v = H_0 D$ , where  $H_0$  is the Hubble constant and  $D$  is proper distance), this boundary occurs at a proper distance of  $D_H = c/H_0$ , which is currently approximately 14.4 billion light-years from Earth.<sup>2</sup>

A common, deeply ingrained misconception is that nothing can recede faster than light, and that the Hubble Sphere therefore represents the ultimate, impenetrable edge of the observable universe.<sup>2</sup> This is categorically false.<sup>10</sup> Special relativity strictly prohibits objects

from moving *through* a local inertial reference frame faster than  $c$ , but it places absolutely no restrictions on the rate at which the metric space *between* two widely separated objects can expand.<sup>3</sup> The expansion of space can effortlessly carry galaxies away from us at superluminal (faster-than-light) speeds.<sup>3</sup>

Remarkably, we can and do routinely observe galaxies that are currently receding from us faster than light, and have always been receding from us faster than light.<sup>3</sup> How is this possible? When a photon is emitted toward Earth by a superluminal galaxy, the photon is initially dragged backward relative to us (its proper distance from Earth increases) because the space it is

traveling through is expanding away from us faster than  $c$ .<sup>2</sup> However, as the universe's expansion history evolves, the Hubble sphere itself expands. Once the expanding Hubble sphere overtakes the struggling photon, the photon enters a region of space that is receding from Earth at subluminal speeds. At this point, the photon can finally make genuine progress toward Earth and eventually reach our telescopes.<sup>2</sup> Thus, the Hubble Sphere is a critical distance marker, but it is not a true event horizon.<sup>2</sup>

## 5.2 The Particle Horizon

The Particle Horizon is the absolute boundary of the observable universe.<sup>45</sup> It represents the maximum comoving distance from which light could have traveled to the observer since the Big Bang.<sup>45</sup> Because the universe has a finite age (approximately 13.8 billion years), light has only had a finite amount of time to travel. Taking the expansion of space into account, the mathematical integration of the photon's path yields a current proper distance to the particle horizon of approximately 46.5 billion light-years.<sup>49</sup>

The particle horizon divides the universe into two stark categories: events we have theoretically seen or could see *today*, and events we cannot yet see.<sup>13</sup> As time progresses, the particle horizon generally expands, bringing new, previously unseen galaxies into our observable universe.<sup>45</sup> It defines our past light cone.<sup>2</sup>

### 5.3 The Cosmological Event Horizon

The Cosmological Event Horizon is the most pertinent boundary regarding the user's query about "lost visibility." Unlike the particle horizon, which deals with the limits of the past, the event horizon deals with the absolute limits of the future.<sup>2</sup>

In a universe dominated by dark energy, the expansion of space is actively accelerating.<sup>9</sup> Because the expansion is accelerating, the Hubble Sphere is shrinking in comoving coordinates. This dynamic leads to the creation of a Cosmological Event Horizon: a hard boundary beyond which a photon emitted *today* will never reach us, no matter how long we wait.<sup>9</sup> The distance between the observer and the photon grows faster than the photon can bridge the gap, forever.<sup>11</sup>

The current proper distance to our cosmological event horizon is approximately 16.5 billion light-years. Any cosmic event that occurs today beyond 16.5 billion light-years is permanently causally disconnected from our future.<sup>9</sup> This is a real, physical event horizon, fundamentally analogous to the event horizon of a black hole, but inverted.<sup>11</sup>

The following table summarizes the distinctions between these three critical cosmological boundaries:

| Horizon Type            | Current Proper Distance   | Physical Definition   | Observational Consequence   |
|-------------------------|---------------------------|---|---|
| <b>Hubble Sphere</b>    | ~14.4 billion light-years | The distance where recession velocity exactly equals the speed of light ( $v = c$ ).                    | We <b>can</b> see light emitted from beyond this sphere. Superluminal recession does not prevent observation. |
| <b>Event Horizon</b>    | ~16.5 billion light-years | The maximum distance from which a photon emitted <i>today</i> can ever reach us in the infinite future. | Defines the limits of our future light cone. Light emitted beyond this line today is permanently "lost."      |
| <b>Particle Horizon</b> | ~46.5 billion             | The maximum   | Defines the   |

|  |             |   |  |
|--|-------------|---|--|
|  | light-years | distance from which light could have traveled to us since the Big Bang. | absolute edge of the observable universe. Defines our past light cone. |
|--|-------------|---|--|

## 6. Lost Visibility: The Optical and Gravitational Fate of Distant Light

When a distant galaxy is swept across the cosmological event horizon due to the accelerating metric expansion of space, what exactly does a local observer see, and what happens to the light that is left behind?

### 6.1 Asymptotic Redshift and the Freezing of Time

The crossing of the cosmological event horizon is not characterized by a sudden visual disappearance. Just as an object falling into a black hole appears to slow down and freeze at the Schwarzschild radius due to infinite gravitational time dilation, a galaxy crossing the cosmological event horizon appears to slow down and freeze in time from our frame of reference.<sup>10</sup>

From our perspective, the light from the galaxy becomes increasingly stretched as it approaches the horizon.<sup>10</sup> As the galaxy approaches the horizon in our reference frame, the

cosmological redshift approaches infinity ( $z \rightarrow \infty$ ).<sup>11</sup> Concurrently, the wavelength of the light approaches infinity, and its energy drops exponentially toward zero. Furthermore, the rate at which we receive individual photons from the galaxy decreases exponentially.

The galaxy simply fades into undetectable irrelevance, redshifted out of the visible spectrum, through the infrared, microwave, and radio bands, until its photons possess wavelengths on the scale of the universe itself, and their individual quantum energy is virtually zero. At this point, the light is, for all observational intents and purposes, "irrelevant because we cannot see it." The light has not stopped moving locally—a hypothetical observer living in that distant galaxy would see their own local space as perfectly normal<sup>31</sup>—but the vast expansion of the intervening space has severed the causal link to Earth.<sup>11</sup>

### 6.2 The Gravitational Accounting of the Unseen

While the light and matter beyond the event horizon may be optically lost to us, does it remain part of the gravitational accounting of the universe? ArcSecs queries whether the unseen light continues to gravitationally influence the cosmos. To answer this, one must rigorously distinguish between the particle horizon and the event horizon, and understand the propagation speed of the gravitational interaction.

According to general relativity, changes in the gravitational field (gravitational waves)

propagate exactly at the speed of light,  $c$ .<sup>45</sup> Consequently, the gravitational reach of any object is subject to the exact same light-cone constraints as electromagnetic radiation.<sup>45</sup>

### Mass Beyond the Particle Horizon

If a mass exists beyond our *particle horizon* (greater than 46.5 billion light-years away), it lies entirely outside our past light cone.<sup>45</sup> This means that neither its light nor its gravitational influence has had enough time since the Big Bang to reach us.<sup>45</sup> We are fundamentally gravitationally blind to anything outside the particle horizon.<sup>45</sup>

While some controversial observational studies (such as anomalous data from the WMAP satellite) have claimed to detect "dark flow"—a coherent bulk motion of galaxy clusters purportedly pulled by the gravitational influence of mass outside the observable universe—standard cosmology staunchly maintains that strict causal disconnection prevents any actual gravitational influence from beyond the particle horizon.<sup>52</sup> If such motions exist, they are generally attributed to pre-inflationary quantum entanglement or statistical anomalies rather than direct, real-time gravitational pulling from beyond the particle horizon.

### Mass Beyond the Event Horizon

The scenario is entirely different for objects that cross the *cosmological event horizon* (16.5 billion light-years away). When a galaxy crosses this threshold, we can no longer receive any new information, light, or gravitational waves emitted by it *from that moment onward*.<sup>12</sup> However, the galaxy has already been emitting light and gravity for billions of years prior to crossing the horizon.<sup>12</sup>

Because gravity propagates at  $c$ , we are constantly bathed in the gravitational influence of the galaxy's past positions.<sup>55</sup> Even as the galaxy's optical image freezes and fades toward infinite redshift, its static gravitational field (which was established in our local region of space long before it crossed the horizon) remains present.<sup>12</sup> We will never feel the gravitational pull of the galaxy as it exists today, but we will forever feel the gravitational pull of its past, asymptotically approaching the exact moment it crossed the horizon.<sup>12</sup>

### The Cosmological Fluid and the Global Stress-Energy Tensor

Furthermore, the light that becomes "lost" to us does not exit the universe; it simply exits our observable patch.<sup>12</sup> The global stress-energy tensor  $T^{\mu\nu}$  that dictates the expansion rate of the entire universe via the Friedmann equations accounts for a homogeneous and isotropic distribution of matter and radiation everywhere, not just what is visible from Earth.<sup>1</sup> The photons that redshift out of our view are simultaneously entering the observable universe of some other distant observer located elsewhere in the cosmos.<sup>10</sup> The radiation density  $\rho_R$  drops strictly as  $a^{-4}$  everywhere, dictating the global curvature and expansion rate.<sup>6</sup> Therefore, the "lost" light absolutely remains part of the gravitational accounting of the

universe. Its energy density, though severely diminished by the scale factor, remains a non-zero, active term in the stress-energy tensor that drives the universe's macro-evolution.<sup>6</sup>

## 7. Thermodynamics and the Fate of Information at the Horizon

To fully and exhaustively address the fate of light beyond the event horizon, we must bridge the macroscopic world of general relativity with the microscopic world of quantum field theory through the thermodynamics of spacetime horizons. In the early 1970s, Stephen Hawking famously proved that black hole event horizons are not entirely black; they possess quantum entropy and emit thermal radiation.<sup>11</sup> Shortly thereafter, in 1977, physicists Gary Gibbons and Stephen Hawking published a landmark paper demonstrating that this thermodynamic framework applies equally to *cosmological* event horizons.<sup>56</sup>

### 7.1 The Gibbons-Hawking Temperature

In a universe dominated by dark energy, spacetime asymptotically approaches a de Sitter geometry. De Sitter space is a highly symmetric solution to Einstein's field equations

characterized by an empty universe with a constant positive cosmological constant ( $\Lambda$ ) and an exponential expansion rate.<sup>61</sup> Gibbons and Hawking showed that an observer in a de Sitter universe is surrounded by a cosmological event horizon that behaves much like an inside-out black hole.<sup>17</sup>

Just as a black hole event horizon prevents light from escaping, a cosmological event horizon prevents light from entering.<sup>12</sup> Because the horizon acts as a causal boundary that permanently hides information from the observer, it possesses an intrinsic quantum entropy proportional to its surface area, adhering to the Bekenstein-Hawking entropy formula.<sup>58</sup>

Furthermore, the cosmological horizon emits a thermal bath of particles, known as Gibbons-Hawking radiation, into the observable universe.<sup>66</sup> The appropriate vacuum state for the quantum field at the horizon is described by the Hartle-Hawking vacuum state.<sup>57</sup> The

temperature of this ambient radiation is directly proportional to the Hubble parameter  $H$  :

$$T_{GH} = \frac{\hbar H}{2\pi k_B}$$

Where  $\hbar$  is the reduced Planck constant and  $k_B$  is the Boltzmann constant.<sup>66</sup> This reveals a profound reality regarding the light that crosses the event horizon. When photons redshift into oblivion and fall beyond the horizon, the information they carry is not destroyed. Instead, it is absorbed by the horizon's entropy.<sup>62</sup> The horizon itself acts as a thermodynamic heat bath.<sup>66</sup>

### 7.2 Backreaction and the Generalized Second Law of Thermodynamics

When light or matter crosses the cosmological event horizon, it exits the observer's causal patch. If one only accounts for the entropy of the observable universe, the disappearance of this light would theoretically decrease the total entropy of the system.<sup>64</sup> To prevent a catastrophic violation of the Second Law of Thermodynamics, physicists rely on the Generalized Second Law, which states that the sum of the entropy of the matter inside the observable universe *and* the entropy of the cosmological horizon must never decrease over time.<sup>62</sup>

When lost light crosses the horizon, it contributes to a quantum "backreaction".<sup>63</sup> The energy and entropy of the lost radiation are absorbed into the thermodynamic properties of the horizon itself.<sup>64</sup> As the universe absorbs this information, the horizon area may slightly adjust (in dynamic, non-perfect de Sitter models) in response to the flux of energy across it, preserving absolute thermodynamic consistency.<sup>62</sup>

Therefore, in the ultimate thermodynamic and quantum mechanical accounting, the lost light is far from irrelevant. Its passage across the boundary is meticulously recorded in the surface area and entropy of the cosmological event horizon.<sup>58</sup> The light becomes part of the thermal bath that defines the very vacuum of space.

## 8. Synthesis and Conclusion

The query posed regarding the expansion of the universe, cosmological redshift, and the ultimate fate of lost visibility demands a highly nuanced resolution that spans classical relativity, differential geometry, and quantum thermodynamics. As spacetime expands, light is unequivocally stretched, its wavelength increases, and its quantum energy irrevocably drops.<sup>6</sup> Based on an exhaustive examination of general relativity, fluid equations of state, cosmic metric boundaries, and horizon thermodynamics, the rigorous conclusions are as follows:

1. **The Fallacy of Global Conserved Energy:** The energy of redshifted light does not physically "go" anywhere, nor is it converted into localized gravitational potential energy. General relativity fundamentally rejects the global conservation of energy in an expanding universe because the dynamic, time-dependent nature of the FLRW metric destroys the time-translation symmetry required by Noether's Theorem.<sup>15</sup> Energy is lost outright, but this loss is not a violation of physics; it is precisely mathematically accounted for by the local conservation of the stress-energy tensor ( $\nabla_{\mu} T^{\mu\nu} = 0$ ) and the continuous scaling of radiation density as  $a^{-4}$ .<sup>6</sup>
2. **Optical Irrelevance vs. Gravitational Relevance:** Light that exists beyond our cosmological event horizon is optically irrelevant because the superluminal expansion of the intervening space ensures its photons will never reach our detectors.<sup>11</sup> The light asymptotes to an infinite redshift, freezing in time at the boundary boundary.<sup>11</sup> However, it is never excluded from the gravitational accounting of the universe.
3. **The Persistence of Gravitational Influence:** The gravitational influence of objects that have crossed the event horizon continues to affect the observer, because the observer remains in the causal future of the object's past states.<sup>12</sup> The gravity emitted before the object crossed the horizon continues to warp local spacetime. Furthermore, on a global

macroscopic scale, the stress-energy tensor that dictates the curvature of the entire cosmos naturally includes the radiation density of that "lost" light, which is propagating normally through its own local, causally disconnected patch of spacetime.<sup>6</sup>

4. **Thermodynamic Integration at the Horizon:** Finally, the boundary that separates the observable from the unobservable—the cosmological event horizon—is not merely a geometric artifact, but a physical, thermodynamic entity.<sup>58</sup> When light crosses this threshold and is lost to visibility, its information and entropy are encoded into the horizon itself. This process strictly upholds the Generalized Second Law of Thermodynamics and contributes to the Gibbons-Hawking temperature of the cosmic vacuum.<sup>62</sup>

In summation, light in an expanding universe may fade from view, stretched to the point of absolute optical imperceptibility, and locked forever behind an impenetrable horizon of expanding space. Yet, it never becomes physically irrelevant. Through local covariant conservation, residual gravitational fields, and quantum horizon thermodynamics, the lost light remains an indelible component of the cosmic fluid, forever contributing to the global curvature of spacetime and the thermal balance of the universe.

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