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A FEATHER FALLS, A HAMMER FALLS

Sensing gravitational waves

FIGURE 1 Aerial view of Virgo. Google Earth, 29/08/2024

Falling in love is not at all the most stupid thing that people do—but gravitation cannot be held responsible for that[1].

[1] Einstein, Albert, Dukas, Helen, Hoffmann, Banesh, Rosenkranz, Ze'ev. *Albert Einstein: The Human Side: Glimpses from His Archives*. Princeton: Princeton University Press, 2016

INTRODUCTION

Two reinforced concrete, vacuum-sealed tunnels plough through the flat wilderness of the Tuscan countryside.

Stretching perpendicularly for three kilometers each, Virgo's arms monitor the distortions elicited by gravitational waves' passage in the landscape of Cascina (PI), detecting changes in the structure of space-time smaller than the diameter of a proton. Here, some of the most infinitesimal variations ever recorded by humankind open a portal into the biggest and most violent events that ever happened in the universe.

Despite its referents being remote in space and time, laser interferometers for gravitational waves detection are deeply oriented towards their local context and entangled in their natural environment. My inquiry takes shape from within this entanglement.

Virgo is one of the three interferometers that since 2015 have been pinpointing gravitational waves as a global network of detectors. I encountered this kilometer-scale interferometer as an assemblage of agencies by conducting fieldwork in its infrastructure(s), talking with the people who operate it and the ones who study its signal (and noise), and exposing myself to its rhythms. Through these encounters, I experienced a distinctive mode of relation with the vastness of the cosmos, defined by continuous processes of calibration and deep, sustained states of vibrational attunement to the interferometer's resonance field.

These practices of attunement suggest that gravitational waves astronomy probes a pervasive field from which signals must be painstakingly extracted. Rather than approaching the gravitational field as the setting of a series of discrete, distant astrophysical events, I attempt to frame it here as an elemental medium[2]: a material and relational substrate that permeates the universe, structuring the motion of masses and spreading information through its continuous modulation.

[2] Peters, John. *The Marvelous Clouds: Toward a Philosophy of Elemental Media*. Chicago: University of Chicago Press, 2015

I propose using the compound term *hypertunement* to describe the epistemic state that emerges in the attempt to probe such an entity. Defined as the process of resonating within a specific vibrational milieu to filter it out as cosmic signal's noise, *hypertunement* refers to a set of practices that I observed within Virgo. It is aimed at orienting the attentiveness in an environment saturated with both signals and disturbances unfolding across radically different space-time scales—one where the collision of two black holes billions of light years away blends into the same register of the passage of a tractor plowing the fields that surround Virgo.

An analysis of *hypertunement*'s operative logics constitutes the core of this thesis. I examine the role of noise as a primary working material, with signal emerging residually as a discrepancy that cannot be traced back to the local environment. The isolation of signal from the continuum of the vibrational landscape allows Virgo's infrastructure to peer into a hyperobject[3]—the gravitational field—massively distributed in space and time relative to the human scale.

[3] Morton, Timothy. *Hyperobjects: Philosophy and Ecology after the End of the World*. Minneapolis: University of Minnesota Press, 2013

Departing from the phenomenological asymmetry of the gravitational field and humankind, I interrogate the limits of *monohumanism*[4] as an epistemic framework. Sylvia Wynter makes use of this term to name the modern regime of knowledge that universalizes a historically specific genre of the human being—autonomous and rational—as the normative subject through which reality becomes intelligible. *Monohumanism* grounds knowledge in the perceptual and cognitive capacities of a masterfully dominant observing subject; instead, I examine how gravitational wave detection yields forms of knowledge that are offloaded across natural elements, infrastructures, algorithms, and trained bodies, asking how these distributed sensing practices impact the way posthuman subjectivities situate themselves cosmologically in a universe where energy and information propagate and resonate far beyond the limits of perception.

[4] Wynter, Sylvia, McKittrick, Katherine. *Unparalleled Catastrophe for Our Species?: Or, to Give Humanness a Different Future: Conversations*. Durham: Duke University Press, 2015

A PARADOXICAL INTIMACY

A falcon feather lies on the surface of the moon.
On August 2nd, 1971, the Apollo 15 Mission Commander, David Scott, replicated Galileo's gravity experiment[5] on the summit of Mount Hadley, in the Moon's northern hemisphere. Towards the end of his third and final walk on the lunar soil, Scott turned to the broadcast camera:

> *In my left hand I have a feather[6]; in my right hand a hammer. I guess one of the reasons we got here today was because of a gentleman named Galileo. A long time ago, he made a rather significant discovery about falling objects in gravity fields; and we thought—where would be a better place to confirm his findings than on the Moon?*[7]

He opened his fists. The hammer and the feather undertook their parallel descent through the faint lunar atmosphere, hitting the ground at the same instant.
As far as it is known, the feather and the hammer still lie there.

A little over ten kilometers from the original site of Galileo's falling bodies experiment (approximately 385,000 kilometers from Mount Hadley) stands one of the most complex technoscientific instruments ever built: Virgo[8]. Alongside the twin interferometers of the LIGO project and KAGRA[9], Virgo deploys laser interferometry to measure differential variations in space-time by tracking changes in the length of its arms.

[2] Between 1589 and 1592, Galileo is said to have dropped two cannon balls of different masses from the leaning tower of Pisa to demonstrate how gravity acts on bodies regardless of their weight. Although the anecdotal authenticity of the experiment is contested, it is certain that Galileo wrote about his hypothesis as a thought experiment that preceded the formulation of the *Legge sulla Caduta dei Gravi* (*Law of Falling Bodies*), after which Newton mathematically formalized the *Law of Universal Gravitation*

[6] The falcon feather belonged to Baggin, the Colorado Springs U.S. Air Force Academy mascot

[7] Scott, David. "Apollo 15 Feather and Hammer Drop." Wikimedia, May 17, 2019. https://commons.wikimedia.org/wiki/File:Apollo_15_feather_and_hammer_drop.ogv

[8] Proposed in the mid 1980s by Italian and French physicists Adalberto Giazzotto and Alain Brillet, Virgo paved the way for EGO (European Gravitational Observatory). Despite its funders jokingly calling it the "Very Improbable Radio-Gravitational Observatory," the laser interferometer was named after a massive cluster of about 1,500 galaxies located in the constellation of Virgo, at 16.5 megaparsec (almost 54 milion light-years) from Earth, where it was first thought a significant amount of gravitational waves signals would have been found

[9] Located in Hanford (Washington) and Livingston (Louisiana), the two interferometers of the LIGO project constitute, with Virgo (Cascina, Italy) and KAGRA (Hida, Japan), the LVK Collaboration—a global network of gravitational waves observatories deployed in a joint production and analysis of data. Because Kagra is far less sensitive than its European and American counterparts, the parallel detection of gravitational events in Virgo and LIGO is essential for the triangulation of cosmic signals, allowing the rise of multi-messenger astronomy

FIGURE 2 Aereal view of Virgo's West Arm, November 2025

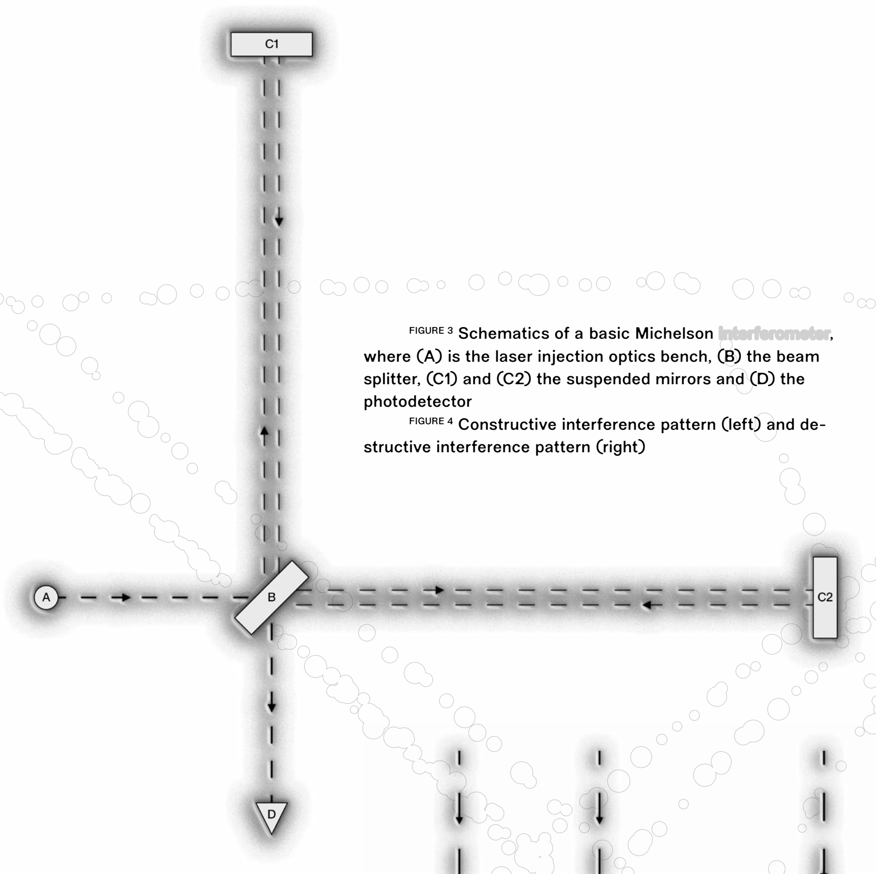

FIGURE 3 Schematics of a basic Michelson interferometer, where (A) is the laser injection optics bench, (B) the beam splitter, (C1) and (C2) the suspended mirrors and (D) the photodetector

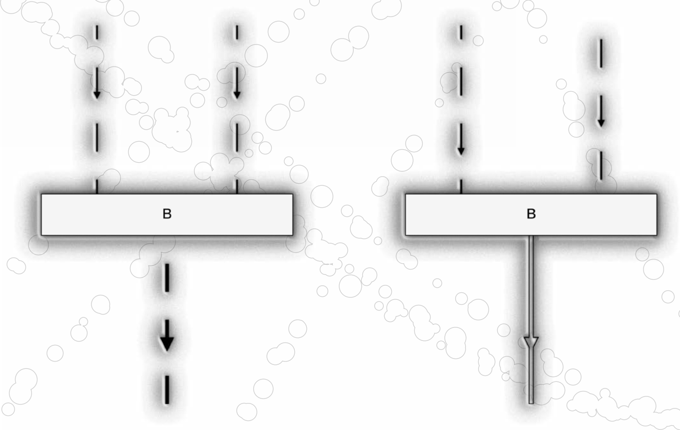

FIGURE 4 Constructive interference pattern (left) and destructive interference pattern (right)

An interferometer is fundamentally a machine engineered to monitor the stability of its own spatial configuration. At its core, a single laser beam (*Figure 3: A*) is split into two (*Figure 3: B*) and sent through perpendicular arms inside ultra-high vacuum tunnels. At the end of each of them, the beams reflect off a suspended mirror (*Figure 3: C1 and C2*) and get recombined in the beam splitter (*Figure 3: B*), to be eventually read by a photodetector (*Figure 3: D*). When a gravitational wave crosses Earth, it stretches and contracts space-time, varying the length of the interferometer's arms alternately and producing a phase shift in the recombined laser beam. This difference generates an optical interference

pattern proportional to the distortion caused by the gravitational wave[10] (*Figure 4*). In this process, Virgo acts as a sensing apparatus, translating cosmic-scale perturbations of space-time into infrastructural variations measurable by a photodetector.

[10] Abbott, Benjamin, et al. "Observation of Gravitational Waves from a Binary Black Hole Merger." *Physical Review Letters* 116, no. 6 (2016)

Gravitational waves revealed by terrestrial observatories are ripples in space-time produced by cataclysmic cosmic events involving massive objects moving at extreme speed. Beyond the possibility of detection from Earth, though, everything with mass undergoing acceleration generates pulses that alter space-time's curvature and the position of any other body within it.

Gravitational waves confront humanity with a perceptual paradox: they incessantly reshape reality—and the foundational conditions for perception—while operating on a continuum of variations that remains fundamentally inaccessible to direct sensing. Inside Virgo, this paradox is negotiated through extensive protocols of calibration and vibrational filtering that render such phenomena perceptible. These practices result in the emergence of a sensorial ecology particular to the infrastructural assemblage of a laser interferometer—one in which perception arises from *hypertunement*.

The history of scientists coming to terms with gravity unfolds through mundane gestures defying common sense: Galileo's cannon balls, Newton's apple, Scott's hammer and feather. These familiar objects expose the profoundly counterintuitive nature of a phenomenon so foundational to the human experience that it often fades into the periphery of perception. Virgo breaks this lineage, expanding the visibility of gravity beyond its meso-scale effects as force and registering it as an ever-evolving, cosmic-scale field. The interferometer's operative logic tunes into gravity as a relational field that structures the universe across scales, fostering a reconsideration of how embodiment foundations lie far beyond bodies' sensorial register.

WHILE ON THE SHORE

It's afternoon. The wind stirs the foliage of cluster pines in a hectic choreography.
They shake their branches as if animated by one distributed brain, invisible in the depths of the sandy soil.
The landscape unfolding in front of them is the infinite separation of the expanse of water—marking a dramatically high horizon—and a sky crossed by immense clouds that are tinted

red in the distance and shift to darker shades of blue and black at the forefront.
By the beach, the surfs crash violently against one another, producing a quiet and monotonous soundscape, like background static noise.
Seagulls stand on the sand in groups of dozens. Every so often, one of them lifts off with a couple of vigorous wingbeats only to float motionless, gliding on the swift air moving from the sea, and land a few seconds later, a few meters away.
Along the shoreline, the sea waves leave behind clusters of white foam that settle and quiver, shaken by the crisp breeze.
Lying on the sand with my eyes closed, I feel the heat coming from the ground on my back, and the front of my body is exposed to gusts of wind.
I am in balance.

FALLING BODIES AND VIBRATING FIELDS

Gravity is one of the most pervasive forces permeating throughout the universe. On Earth, its effects have been ubiquitous in biological evolution, structuring morphologies, physiologies, and behaviors of all living beings.[11] Humans' ability to orient, balance, and sense their own bodies is also closely tied to the discrete magnitude of the gravitational field on Earth.[12]

[11] Gravity has acted as a persistent selective pressure throughout biological evolution. Its influence is evident in the emergence of structural support systems (such as skeletons, lignified tissues in plants, and cellular cytoskeletons), in mechanisms of orientation and balance (vestibular systems, statoliths in plants, gravitaxis in microorganisms), and in circulatory and respiratory architectures adapted to vertical pressure gradients in terrestrial organisms. Gravity has also shaped locomotion strategies, body size limits, and energy expenditure, favoring specific morphologies in aquatic versus terrestrial environments. Narayanan, Anand S. "Gravity's Effect on Biology" *Frontiers in Physiology* 14 (July 2023)

[12] Parkhurst, Aaron, Jeevendrampillai, David. "Towards an Anthropology of Gravity: Emotion and Embodiment in Microgravity Environments." *Emotion, Space and Society* 35 (May 2020)

This paradoxical intimacy with gravity has informed the history of gravitational theories since their early formulations, eliciting radical conceptual and experimental frameworks to peer beyond the banality of an omnipresent phenomenon that withdraws from perception even as it conditions perceptual processes.

Galileo and Newton understood gravity as an instantaneous pull between masses. Their theories were grounded in approximations that proved sufficient for describing the free-fall of objects but couldn't offer convincing accounts for anomalies in planetary motions or explanations for how gravitational influence propagates through space. Gravity was modeled as a force acting on everything everywhere at once, without any delay, directly proportional to the mass of the bodies involved and inversely proportional to their squared distance.[13]

[13] In Isaac Newton's 1687 fromulation: $F = (m^1 \times m^2) / r^2$, where F is the gravitational pull acting between two bodies, m_1 and m_2 are the masses of the bodies, r is the distance between the centers of their masses, and G is the gravitational constant (on Earth ≈ 9,81 m/s²)

[14] In 1905, Albert Einstein published in the *Annalen der Physik* (*Annals of Physics*) four papers constituting major contributions to the foundation of modern physics, revolutionizing science's understanding of the fundamental concepts of space, time, mass, and energy

[15] While nobody has been able to disentangle her individual contribution to the four *annus mirabilis* papers, I believe it's important to linger for a moment on the role that Mileva Marić—Albert Einstein's first wife—played in their formulation. Much has been written over the past few decades about their collaboration and relationship, with readings of Marić's role ranging from unsigned co-author to sounding board, glorified assistant, unglorified housewife and even the one who made it all possible. A thorough analysis of the nature and magnitude of Marić's contribution lies beyond the scope of this thesis. Nonetheless, I want to acknowledge how their letters and numerous testimonies presented in the books dedicated to her provide substantial evidence of how, at the very least, she supported him intellectually and emotionally throughout the early years of his rise, starting in 1986 as a physics student and until 1914

[16] Misner, Charles, Thorne, Kip, Wheeler, John. *Gravitation*. San Francisco: W. H. Freeman, 1973

In 1915—ten years after the *annus mirabilis* of Special Relativity[14, 15]—scientist Albert Einstein formulated the field equations of General Relativity: he abandoned the notion of gravity as a force and reconceptualized it as a geometric property of space-time itself. Masses would no longer be thought to exert attraction across distance; instead, they would move following the curvature of the gravitational field, co-defined by their dynamic and unceasing interplay with space-time. In the framework of General Relativity, "geometry tells matter how to move, and matter tells geometry how to bend."[16] A corollary to this perspective is a conception of the cosmos as an entangled network, within which every body (a) deforms the local geometry of space-time with its mass, and (b) moves along trajectories defined by the curvature of space-time. Gravity informs the material and relational form of the universe, defining an infrastructural condition of existence for space-time.

One of the most counterintuitive implications of General Relativity is the existence of gravitational waves. Even though Einstein himself initially disregarded them as a mathematical artifact of field equations, they represent the universe's response to the urgency of readjusting its geometry upon changes in the distribution of masses.

If the orbit of every celestial body is shaped by the curvature of the gravitational field, when a mass undergoes variations, the gravitational waves produced by the event propagate outward through the cosmos, readjusting the geometry of space-time and the position of everything within it. In this sense, it is possible to imagine the gravitational field—with the waves sweeping through it at the speed of light—as a form of abiotic echolocation[17] infrastructurally embedded in the universe.

[13] "Echolocation is a process involving the production of sound and the reception of echoes that return from objects. By comparing the outgoing pulse with the returning echoes—which are modified versions of the outgoing pulse—the brain can produce images of the surroundings". Jones, Gareth. "Echolocation." *Current Biology* 13 (July 2005). I mobilize this concept to probe the orientational role that gravitational waves play in the universe's energetic metabolism. My attempt is to frame them as messengers allowing celestial bodies to "position" themselves within an ever-changing gravitational configuration

Unlike electromagnetic radiation, gravitational waves do not travel *through* space-time; they are oscillations *of* space-time. Their interaction with matter is extraordinarily weak, allowing them to traverse the universe largely unimpeded, carrying information about the evolving state of their sources across vast cosmic distances with minimal distortion or attenuation. While making gravitational waves extraordinary high-fidelity messengers, the faintness of their interaction with matter renders them extremely challenging to detect. Everything in the universe—from stars to atoms—expands and contracts rhythmically in an undulatory motion that eludes the domain of any possible sensing organ, as they, too, participate in the contractions and expansions of space-time.

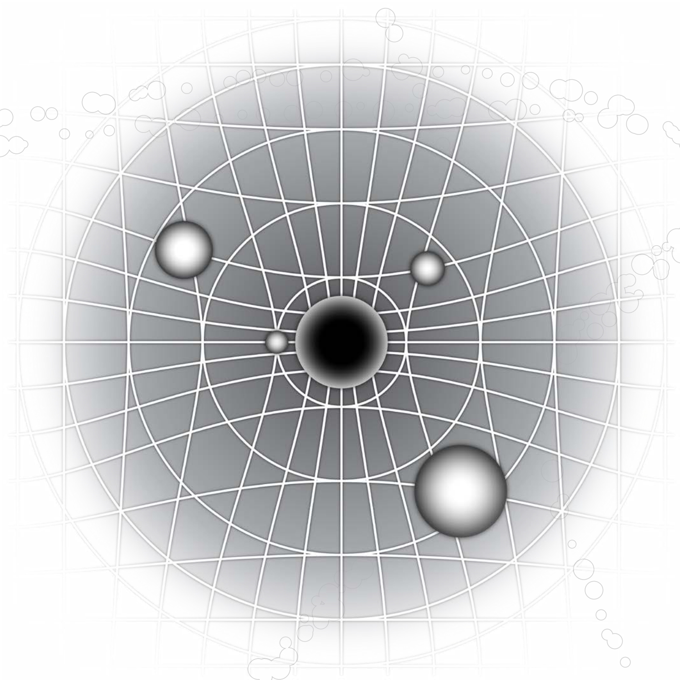

FIGURE 5.1 Visualization of space-time's topology before a mass variation

Gravitational waves' effect on matter is so minute that, when passing through Earth, they stretch and squeeze space-time by magnitudes of 10^{-20}: less than one ten-thousandth the width of a proton. For a century after their prediction, gravitational waves remained a theoretical consequence of General Relativity, mathematically robust yet empirically elusive.

ELEMENTAL MEDIALITY OF GRAVITY

Describing space-time as an infrastructure mediating the spread of information about the mutual position of celestial bodies opens up a definition of the gravitational field as an elemental medium, a "pre-critical notion of media" conceptualized as natural systems of information transmission, enabling forms of interaction between different elements of nat-

ural environments.[18] In *The Marvelous Clouds*, John Durham Peters proposes a definition of media that bleeds out of the technical communication paradigms addressed by media theory. Air carries sound, water sustains life, clouds circulate energy: all these elements represent environmental substrates facilitating a variety of forms of interaction among biotic and abiotic entities.

[18] Peters, John. *The Marvelous Clouds: Toward a Philosophy of Elemental Media*. Chicago: University of Chicago Press, 2015

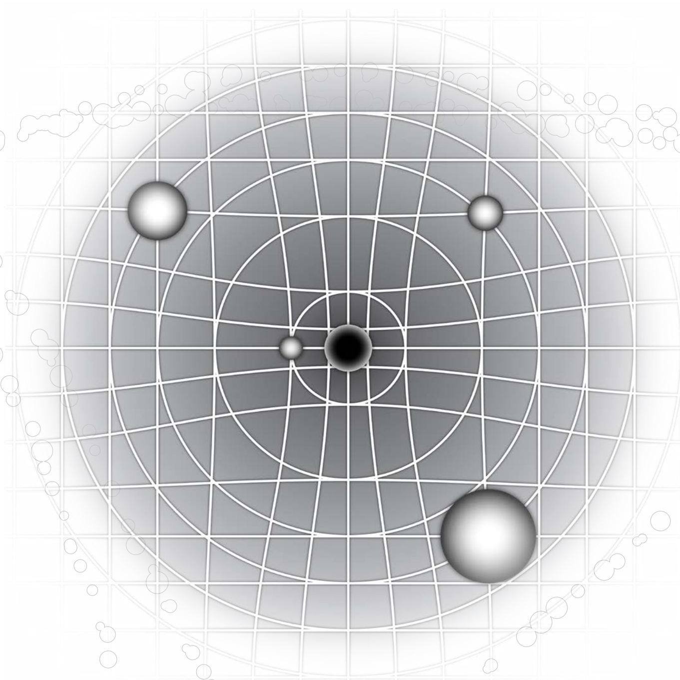

FIGURE 5.2 Visualization of space-time's topology after a mass variation

From this perspective, media are not only defined by the information they carry, but also by the material conditions they establish for relations to occur. They operate prior to meaning, structuring a field in which meaning can later emerge.

Extending this framework to cosmology, the relationships between masses in the universe can "be interpreted not just alongside the domains of matter and energy, but also that of meaning. Hence, ecologies have affordances of semiotic media."[19]

[19] Likavčan, Lukáš. "Light, Metabolisms, Elemental Media: Theorising Human Mediality in the Anthropocene." *Visual Resources* 38, no. 1 (2022)

Gravitational waves appear as paradigmatic expressions of the nature of elemental media. As two black holes merge, they don't encode a message into the gravitational field: the propagation of information is a byproduct of the conversion of mass into energy, which displaces space-time towards its new topology. Gravitational waves redistribute energy from high-entropy systems, evenly spreading traces about their evolving state throughout the cosmos. What propagates is residual information inherent to the universe's energetic metabolism.

Marshall McLuhan's oft-cited formula "the medium is the message"[20] acquires here a literal connotation, as gravitational waves are deformations materially and conceptually inseparable from their medium. This coincidence destabilizes classical communication models that presuppose a distinction between medium, signal, and noise. In the case of gravitational waves, there is no medium external to the phenomenon: the wave is the medium's self-variation.

[20] McLuhan, Marshall. *Understanding Media: The Extensions of Man.* Cambridge: The MIT Press, 1994

The distinction between signal and noise is troubled as well. Space-time is a dynamic medium, wherein sources and disturbances influence each other in a feedback loop. Perturbations—produced by events ranging from the cataclysmic mergers of black holes to the orbital motions of planets—saturate space-time with fluctuations, hence every detection stands out against the backdrop of an ever-vibrating field. Noise constitutes an intrinsic component of that field, and its distinction from signal does not exist prior to detection: noise and signal are qualitatively indistinguishable entities that get separated through the filtering, modeling, and interpretative operations by which interferometers extract a discrete event from an ever-changing continuum.

WHILE IN THE ARM

FIGURE 6 View of the vacuum-sealed tube inside Virgo's West Arm, November 2025

The sky is bright and clear and blue—so blue it seems like a mirror fogged at its edges by the atmosphere and illuminated, at its center, by the blurred, radiant shape of the sun—a mirror nestled in the dark profile of the Apuan Alps, reflecting

in its flatness the color of the metal roof that covers Virgo's kilometer-long arms.
Outside the Central Building, the wind blows even stronger and flutters a fleet of flags, producing a sound reminiscent of the bells tied around cows' necks in the mountains.
As I walk towards the Main Building, I notice the door of the West tunnel is open—every Tuesday morning Virgo is "unlocked"[21] for commissioning works, and it is possible to access almost any space within the interferometer.
I enter the arm.
It's not the first time I've seen the inside of one of the tunnels, but being here alone gives me a sense of awe. I close the door behind me and stand in the dark for a few moments.
I hear the wind: it gusts and reverberates through the corridor.
I hear the low hum of the vacuum pumps and the frantic, metallic clinking of the cables suspending the flags in the distance.
I hear an undefinable background noise saturating the air, seemingly radiating from the tube in which the laser travels.
I turn on the light.
The flickering neons flood that empty, infinite darkness with a greenish light, revealing the liminal monotony of a landscape of concrete and iron. I can't help but feel a sense of isolation, and it almost seems as if I've been transported into an otherworldly dimension.
Everything is surreal in its repetition, stretching as far as the eye can see, in a recurring pattern marked by the ridges on the floor, the lamps hanging from the ceiling, the joints of the vacuum tube and the sheets of the metal roof.
Suddenly I feel hyper-conscious about all the sounds that my body produces.
I hear the hissing of my breath, the clicking of my articulations, the frantic pulse of my heartbeat resonating in my chest.
Still dazed by the whistling wind echoing in my ears, I find myself greeted, at the entrance of the cafeteria, by the now-familiar triptych of photographs decorating the room. Each one portrays a stone where a word has been engraved in serif, capital letters.
Onda. Wave. Vague.

[21] The term unlocked defines the status of the interferometer when one or more of its sub-systems are displaced from their functioning regime and Virgo is therefore unable to acquire data

CYBERNETICS OF *HYPERTUNEMENT*

A laser interferometer needs to undergo continuous calibration to detect the passage of gravitational waves. To reveal the infinitesimal contractions and expansions elicited by the readjustments of the gravitational field's curvature, Virgo must be able to filter out all the vibrations—of far greater magnitude—related to its local environment: the minute tremors of the ground, the hum of the traffic in the distance, the oscillation of the residual air molecules inside the tubes and even the tremble of its own machinery. Seismic activity, thermal expansion, acoustic vibrations, electromagnetic interference, atmospheric pressure variations, and quantum fluctuations of the laser must therefore be attenuated or subtracted.

The interferometer is entangled in an ecology of sensors involved in digital and mechanical protocols aimed at maintaining a state of selective opacity. This state stands at the core of *hypertunement*'s operative logic: control room operators develop a form of attentiveness that is not oriented towards a direct recognition of gravitational waveforms, but rather towards an understanding of the relationality of the interferometer's photodetector signal with those of all the other sensors. The first epistemological gesture in gravitational waves detection is a diagnostic one, aimed at assessing the sensitivity of the machine.

On my last day at Virgo, I followed control room operator Cecilia Zaza during an evening shift.

> *The first thing I look at is the sensitivity range, which should be around 60 megaparsecs: if that's the case, the interferometer is locked and data acquisition can proceed. If the range is at zero, I need to intervene. I check whether the laser is correctly reaching [various points of the optical bench at] injection through an array of camera feeds.*
>
> *Then, I look at the signals coming from the photodiodes at the end of the arms to check if they're locked. I know that if the laser reaches those photodiodes below a certain power threshold, the arms will never reach the lock state [through automated routines], hence I need to manually realign the mirrors.* Before doing that, I look at the DMS22 and access the history of the signals recorded by Virgo's sensors through a program called Data Display. This allows me to hypothesize what caused the unlock, and to activate the proper protocol to get back to it. [...]
>
> *[If none of the routines works,] I can manually realign the mirrors using a software that gives me control over their position and orientation. Once it's done, it begins a phase in which automation takes over, and Virgo starts reducing all the offsets it created [to lock each of its components independently].*[23]

[23] Extracted from a conversation with Cecilia Zaza inside Virgo's control room on 21/11/2025

In the framework of hypertunement, noise—the data

streams detected by local sensors—represents a primary working material, as it must be characterized, modeled, and continuously accounted for. On the other side of the spectrum, signal appears by subtracting known forms of disturbance from a saturated field. The relation between signal and noise, in the context of a laser interferometer, foregrounds the relational nature of the knowledge produced within it: gravitational waves are not known for what they are, but for what they are not. They emerge residually, as discrepancies that cannot be traced back to the local environment.

The processes of calibration granting Virgo's sensitivity destabilize, even at mesoscales, the idea of an absolute observer. *Hypertunement*'s logics resonate with Karen Barad's notion of *intra-action*, defining

> *The mutual constitution of entangled agencies. [...] In contrast to the usual 'interaction', which assumes that there are separate individual agencies that precede their interaction, the notion of intra-action recognizes that distinct agencies do not precede, but rather emerge through, their intra-action.*[24]

[24] Barad, Karen. *Meeting the universe halfway: Quantum Physics and the entanglement of matter and meaning.* Durham: Duke University Press, 2007

From this agential realist framework's perspective, gravitational waves come to exist as objects of knowledge through specific material-discursive arrangements, always and only in the moment of detection: their agency and Virgo's one become intelligible only in relation to their mutual entanglement. Furthermore, since the conditions enacted by the interferometer are situated—with Virgo's sensitivity being shaped by its geographical location, its geological substrate, its climate, and the infrastructural histories sedimented into its design—detection is not universal but local, even when its referent is cosmic.

As David Cecchetto argues in *Humanesis: Sound and Technological Posthumanism*,

> *Technologies today can no longer be adequately thought through the lens of 'extension' but must instead be understood as profoundly implicated in our being. That is, technologies are not tools that we use, nor objects in relation to which we are servomechanisms, but are rather pathways through a relational ontology.*[25]

[24] Cecchetto, David. "Humanesis: Sound and Technological Posthumanism." *Posthumanities* 25. Minneapolis: University of Minnesota Press, 2013

The *intra-action* of the gravitational field and a laser interferometer—understood as a distributed, situated architecture of sensing, where cognition is scattered across a variety of human, natural, and technological actors—defines an ever-evolving configuration that co-produce subjects, objects, and modes of knowing rather than mediating between pre-existing entities. The posthuman subject yielded within such technoscientific milieu depends on a continuous negotiation of its own uncertainty. The ecology of Virgo and its practitioners structurally embodies this uncertainty: as control room operator and optics physicist Maddalena Mantovani put it to me,

> *We studied the local resonance field, we simulated the ways it may couple with the interferometer's signal; yet we simulated what we imagined might happen. Reality is always more complex, so a lot of things will occur that we couldn't have anticipated. We try to foresee everything, but obviously can't.*[26]

[26] Extracted from a conversation with optics physicist Maddalena Mantovani inside Virgo's Main Building on 17/11/2025

The interferometer mirrors the epistemological condition that humans hold towards the gravitational field—one characterized by indirect access, delayed intelligibility, and radical asymmetry of scale. Such framing complicates any positivist assertion on objectivity: the gravitational field remains epistemically opaque, even as it becomes experimentally accessible. What surfaces is not certainty, but a mode of coexistence with uncertainty.

Crucially, uncertainty is not a failure of the apparatus, but its very condition of possibility. As such, it informs the practitioner's archetype produced by gravitational waves astronomy. Scientists inside Virgo interface with the gravitational field's effects as metabolized by a situated, fragile, and continuously calibrated system: they engage with a layered assemblage in which cosmic signals and local resonances are inseparably entangled.

> *When we say that Virgo's signal is very noisy [...], it means that from our perspective the intensity of noise is large compared to signal. [...] This relationship is quantified as signal-to-noise ratio: generally, a detection is considered reliable when this ratio becomes greater than 8:1, 10:1.*
>
> *Rather than reading [Virgo's signal] directly, then, we listen to the information coming from other sensors in relation to it — environmental and anthropic disturbances, infrastructural noise, quantum fluctuations, ... If there is a correlation [...], we can use the sensors' signal to subtract it as noise from the interferometer's one.*[27]

[27] Extracted from a conversation with astrophysicist Giancarlo Cella inside Virgo's Main Building on 18/11/2025

In a laser interferometer, the scientific practice unfolds by orienting attention towards the infrastructure's response to gravitational events, establishing those responses as proxies for cosmic processes. Practitioners are trained by the interferometer, attuned to its rhythms, and informed by its sensitivities: the epistemic subject emerging within Virgo is therefore relational and distributed.

SENSORIAL ECOLOGY OF A GRAVITY WAVE

On September 14th, 2015, the gravitational waves produced by a black hole merger—after having stretched and contracted space-time while traveling for 1.3 billion years—passed through Earth, where they contracted and stretched the kilometer-long arms of the LIGO interferometers, and soon after of Virgo, producing a signal that marked the first detection of a gravity wave in human history—GW150914.[28] The scientific community accepted the detection as "it matched the waveform predicted by General Relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole"[29]: a theoretically predicted, simulated waveform validated the measurement of a sensorially inaccessible event, which in turn confirmed the physical theory that had legitimized it—namely General Relativity. This validation feedback loop allowed the ontological stabilization of gravitational waves: from hypothetical entities, discussed in mathematical terms as abstract components of General Relativity, they acquired the status of real objects, experimentally verified and discussed through a sonic metaphor.

[28] GW150914 Press Release, "LIGO Opens New Window on the Universe with Observation of Gravitational Waves from Colliding Black Holes," LIGO Laboratory (Caltech/MIT), February 11, 2016, https://www.ligo.caltech.edu/page/press-release-gw150914

[29] Abbott, Benjamin, et al. "Observation of Gravitational Waves from a Binary Black Hole Merger." *Physical Review Letters* 116, no. 6 (2016)

GW150914's waveform has been sonified and presented acoustically as a chirp—a sound wave with rapidly ascending frequency. This gesture marked the beginning of a tradition of sonic disseminations for results achieved in gravitational wave physics. This re-mediation does not represent a necessary or natural outcome of the analysis of the signal produced by the passage of gravitational waves, as they're not pressure waves traveling in space-time, like acoustic waves, but deformations of space-time.

Sonification is also an atypical articulation, considering the privileged relationship that astrophysics has historically held with vision. Coincidentally, the range of wavelengths to which terrestrial gravitational wave observatories are most sensitive can be precisely mapped onto the one perceivable by humans through hearing.[30]

Unlike the standard extension of a human sensorial faculty beyond biological limits—the representation as an image or graph of electromagnetic radiation with a wavelength shorter than infrared or longer than ultraviolet—here, an unprecedented sensoriality is transferred into a human perceptual register that prominently features temporality and relationality.

The universe, it was said, has grown ears.[31]

[30] National Science Foundation (NSF). "LIGO Detects Gravitational Waves." Press conference, National Press Club, Washington, D.C., February 11, 2016. http://mediaassets.caltech.edu/gwave

[31] The quote was stated by Columbia University professor and LIGO researcher Szabolcs Marka: "Everything else in astronomy is like the eye, finally, astronomy grew ears. We never had ears before." Overbye, Dennis. "Gravitational Waves Detected, Confirming Einstein's Theory." New York Times, February 15, 2016. https://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html

FIGURE 7 Virgo's North Arm, November 2025

Sonification doesn't reveal an already-existing acoustic dimension of the cosmos; it constitutes an articulation layer through which hypertuned infrastructures become perceptually legible to human operators.

Rendering interferometric data as sounds presupposes several epistemic commitments in the field of gravitational waves physics: that (a) temporal variation is a privileged carrier of meaning and that (b) pattern recognition unfolds effectively through auditory perception. In this sense, sonification acts less as representation than as an epistemic gesture, in which the ear supplements a distributed sensorial ecology where cognition is offloaded across bodies, simulations, and machines.

This acoustic turn resonates structurally with the logic of *hypertunement*. Unlike vision, sound requires co-presence: it situates the listener within the phenomenon, enveloping rather than describing from the distance. From this perspective, sonification aligns with the ontology of gravitational waves themselves—events that cannot be captured frozen in time but only tracked as transient distortions propagating across space-time.

THE GEOMETRY WE FALL THROUGH

This thesis springs from a paradox: gravity's visceral effects make it one of the most intimate universe-structuring forces; yet its workings, for how mundane, remain counterintuitive. Gravitational waves radicalize this paradoxical condition, withdrawing from conscious awareness as they incessantly cross the cosmos modulating the topology of space-time.

I haven't approached this problem as a representational one—how to see, or to *hear* gravity—but rather as an epistemological one: under which material, ecological and infrastructural conditions can gravity be known at all?

I have argued that gravitational waves astronomy produces a distinctive epistemic state, which I have termed *hypertunement*, naming an assemblage of practices meant to resonate within a vibrational milieu so saturated that signal can only appear as what resists identification in the local environment—a mode of knowledge grounded in a selective opacity where certainty is always provisional and relational.

Laser interferometers' operative logics yield forms of sensitivity towards the gravitational field framed as an elemental medium. Ubiquitous forces as gravity unconsciously precipitate onto the living (human) experience through the way they affect the rhythms, temporalities, and embodied experiences of being. Inside Virgo, these forces become for a moment intelligible for a posthuman subjectivity whose processes of sensing and intellection are distributed across humans, machines, infrastructures, and environments.

I opened this thesis with a sentence that Albert Einstein scribbled on a letter he received in 1933. In that letter, a student was asking him whether "it was while upside down, standing on their heads, that people fell in love and did other foolish things." I instinctively wrote this sentence down as I encountered it, almost giggling, and it has since accompanied my inquiry into gravitational waves. There is something quite poetic, and perhaps a bit silly, in the image of people moving around upside down, with a flipped world unfolding to their senses, anchored to humanity by their feelings despite the absurdity of the situation.

Einstein's conviction that gravitation can't be held responsible for people falling in love might sound very reasonable, if not self-evident, and yet it rests on a sharply partitioned understanding of the universe where cosmic forces merely set a stage for experience without partaking in its unfolding. If taken seriously enough—at least on an ontological plane—that image hints at something more subtle: the idea that perception can't be truly understood as independent from the material conditions that inform it. In other words, perception does not pre-exist those conditions as an absolute ontological category, but rather emerges from the interaction of matter and energy in the field where experience unfolds.

Gravity might not determine emotions, nor cause affection, arousal, or love; but it continuously reshapes the spatial and temporal coordinates through which experience unravels, making all of the above recognizable in the forms we know.

What we call human experience is informed by the infrastructural conditions of a universe where past events—former configurations of mass and energy—persist materially, propagating as distortions of space-time; a universe that resonates far beyond the perceptual reaches it informs.

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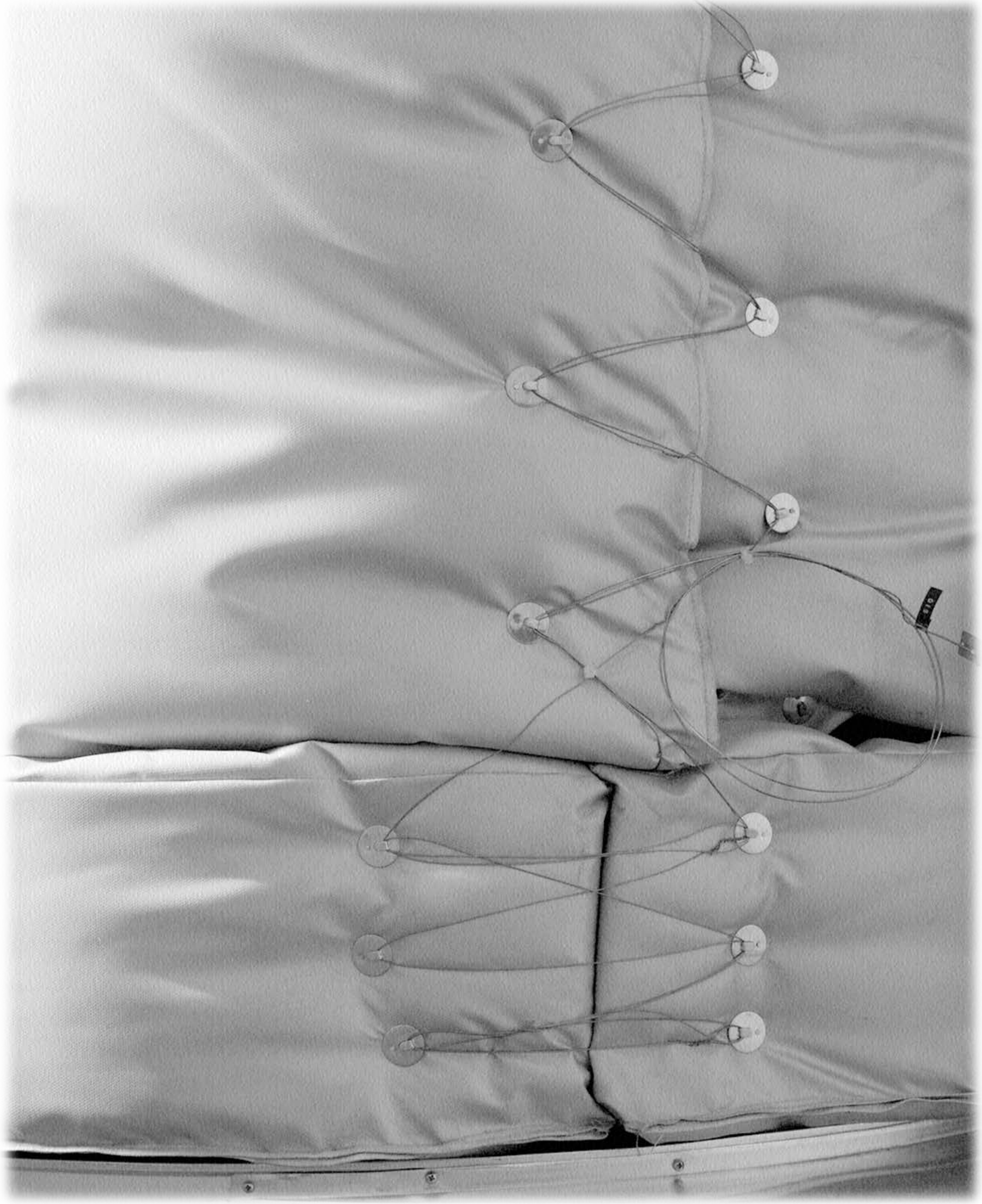

FIGURE 8 **Thermically insulated joint inside Virgo's North Arm, November 2025**