Research Campaign:

Lunar Gravitational-wave Antenna

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EXECUTIVE SUMMARY

The Lunar Gravitational-wave Antenna (LGWA) is a mission conceived as a network of stations to measure the vibrations of the Moon caused by gravitational waves (GWs). The long-term vision is to accomplish ground-breaking, paradigm shifting science in the coming decades on the Moon. LGWA will lead to the first observation of GW signals in the decihertz band greatly expanding our understanding of the universe and laying out a path to eventually probe the moment of its creation. LGWA stations will also be unique contributions to a lunar geophysical network shedding light on the Moon's formation history. LGWA is a project of inclusion and international collaboration, where space-faring and space-aspiring nations can contribute to the LGWA network with their own stations whose cost depends on the targeted station lifetime and deployment location. With respect to the baseline concept proposed here, different sensor technologies can be implemented over time with the goal to continually increase the performance of the LGWA network. The broader context of lunar GW detection and its long-term vision are outlined in an accompanying topical white paper [1].

MISSION CONCEPT

The Lunar Gravitational-wave Antenna (LGWA) is a mission concept to measure the vibrations of the Moon caused by GWs [2]. Its observation band reaches from 1 mHz to several Hz, with peak sensitivity in the decihertz band. It will therefore provide the "missing link" [3, 4] complementing the approved Laser Interferometer Space Antenna (LISA) [5], which will observe below the decihertz band, and future ground-based detectors like the proposed Cosmic Explorer (CE) [6] and Einstein Telescope (ET) [7], whose observation bands lie above a few Hertz; see figure 1.

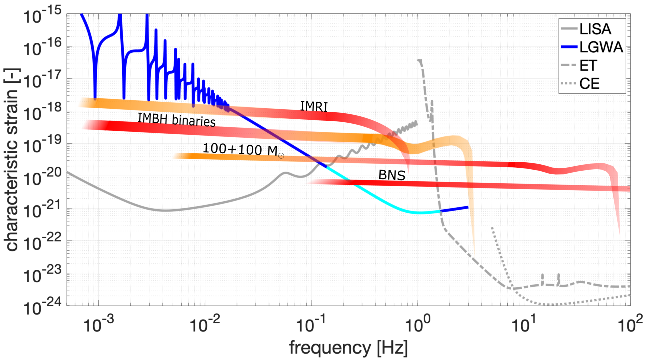

FIG. 1. Characteristic strain sensitivities for the Laser Interferometer Space Antenna (LISA), LGWA and the terrestrial detectors Einstein Telescope (ET) and Cosmic Explorer (CE). A few reference signal spectra are added to the plot for comparison: inspiral and merger of an intermediate-mass binary black hole at 2 Gpc (SNR = 50 for LGWA), an intermediate-mass ratio inspiral at 830 Mpc (SNR = 100), and a 100+100 $M_\odot$ binary black hole at 412 Mpc (SNR = 10). Traces represent up to 5 years of frequency evolution of the signals.

The high scientific revenue expected from observations in the decihertz band led to the proposals of technologically ambitious missions like Big Bang Observer [8] and DECIGO [9]. The LGWA mission concept is inherited from the Lunar Surface Gravimeter deployed in 1977 on the Moon with Apollo 17 [10]. Two components of LGWA are crucial for its success as a ground-breaking decihertz GW observatory [2]:

FIG. 2. Star-like deployment configuration of four LGWA stations in a kilometer-scale array equipped with cryogenic inertial sensors. The LGWA deployment site is one of the permanently shadowed regions inside a crater at the lunar north or south pole. A laser-power beaming system is shown as a possible power system for LGWA [11].

1. a cryogenic inertial sensor concept for the measurement of horizontal ground displacements reaching femtometer sensitivity at 1 Hz [12];

2. deployment of a kilometer-scale array of at least four inertial sensors (see figure 2) and using advanced noise-cancellation techniques for the reduction of seismic background noise in the decihertz band [13]. At least four stations are required to create a configuration of one sensor being surrounded by other sensors in all directions for efficient noise cancellation [14, 15]. In fact, *any* lunar detector targeting the decihertz band requires an array of LGWA-grade inertial sensors to reduce the seismic background noise, since the background is random in nature and can only be analyzed with locally acquired array data.

Deployment and operation: LGWA sensors need to be deployed on the ground inside a permanently shadowed region (PSR) whose natural cryogenic environment leads to improved sensitivity of the inertial sensors and also eliminates thermal noise and seismic disturbances induced by solar radiation [16, 17]. The targeted lifetime of LGWA is 10 year, which benefits the science outcome especially with respect to the observation of rare events, and which is long enough to be able to extend the network beyond the baseline configuration proposed here. We propose a deployment of all LGWA stations with a single lander. A rover or astronauts lay out the array with fiber connections between LGWA stations and lander for powering and data transfer, where the power source (radioisotope thermoelectric generator [18] or receiver panel of a power beaming system [11]) and communication relay are located. The power consumption per LGWA station will be around 15 W, and the mass of the LGWA inertial sensor, platform (including leveling system and drill), dust shield, and cryocooler will be around 12 kg. An array of four LGWA stations will produce about 250 Mbits of data per day.

LGWA Soundcheck: Before the LGWA deployment, a pathfinder mission under the name LGWA Soundcheck is proposed consisting of the deployment of an advanced inertial sensor for measurements of horizontal surface vibrations inside a PSR. The main goals of LGWA Soundcheck are technology demonstration and the characterization of the seismic environment at the foreseen LGWA deployment site. It will be the first sensor deployed on the Moon to characterize the seismic environment in a PSR and provide a first image of the PSR shallow regolith texture, crucial for the definition of the best LGWA deployment method. LGWA Soundcheck will operate at PSR environmental temperatures ($\sim$ 40 K) with a targeted lifetime of several weeks powered by battery. The sensor can be mounted on the lander as is done for the Farside Seismic Suite [19] and therefore is compatible as payload for the CLPS-PRISM program.

KEY SCIENCE OBJECTIVES

As decihertz GW detector, LGWA has access to a unique band of masses and energies of GW sources, which cannot be studied by other GW detectors at high signal-to-noise ratio and out to high redshift. The decihertz band is of prime interest to cosmological studies, fundamental physics, and astrophysics [3, 20–23]. A graphical summary of LGWA science is shown in figure 3. As link between space-borne and ground-based detectors, LGWA is an ideal partner for *multiband studies* where these detectors observe the same GW signals at different phases of their frequency evolution [22, 24, 25]. Also, the wealth of astrophysical sources observable by LGWA containing binaries with white dwarfs and neutron stars, tidal disruption events, or massive and supermassive black holes with accretion disks leads to a rich *multi-messenger science* case.

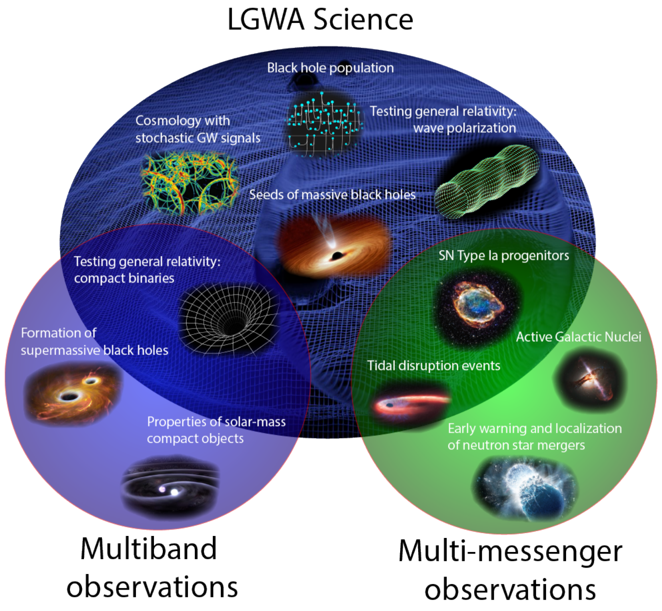

FIG. 3. Graphical summary of the LGWA science case including multi-messenger studies with electromagnetic observatories and multiband observations with space-borne and ground-based GW detectors.

Cosmology and the early Universe: One of the first proposed decihertz GW detector concepts was the Big Bang Observer, whose NASA-led mission concept study clearly pointed out the unique role of the decihertz band for observations of a primordial GW background [8, 26]. Deployments of LGWA stations at both lunar poles, while not foreseen for the LGWA baseline configuration, would enable extremely sensitive searches for such backgrounds by correlating data from antipodal station pairs [27, 28]. A possible source of primordial GWs at decihertz are first-order phase transitions in the early universe at TeV energies [29].

LGWA will also shed light on the mystery how supermassive black holes were able to form within only 1 Gyr after the production of matter [30, 31]. The exploration of the entire formation history of supermassive black holes starting with their early seeds requires the observation of the entire range of black-hole masses to high redshift including the massive and intermediate-mass regime covered by LGWA as shown in figure 4.

Fundamental physics: In GW science, fundamental physics can be probed by searching for deviations in waveforms of compact binaries from waveform models based on general relativity [32]. Estimation of waveforms and their parameter values can be greatly improved by exploiting multiband observations [25, 33–35]. LGWA as decihertz detector will be an ideal partner observatory of space-borne and ground-based GW detectors for these studies.

LGWA can also be used to probe the polarization content of a GW, which is another way to search for

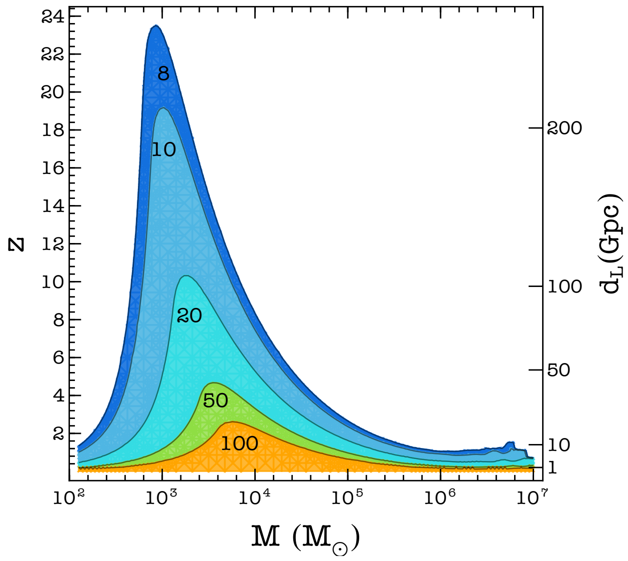

FIG. 4. The plot shows contours of constant SNR as a function of redshift z and total (source-frame) mass of a BBH. The BBHs are assumed to be optimally located and oriented, which means that the SNR $= 8$ contour indicates the LGWA detection horizon.

deviations from general relativity. It requires additional LGWA station deployments on the surface of the Moon, which should be widely separated from each other [36, 37]. This necessarily means that some stations of such a network cannot operate in a PSR, which requires a different sensor design.

Astrophysics: LGWA will be able to observe inspirals and mergers of white-dwarf binaries, which emit GWs in the decihertz band. Such a merger is a possible progenitor of supernovae (SN) type Ia [2, 3, 21]. Observation of a white-dwarf merger with a SN Ia would mark a breakthrough in our understanding of these sources, which play an important role for the construction of the cosmic distance ladder [38].

The merger of two neutron stars is associated with a kilonova and the emission of gamma-ray bursts [39]. LGWA can observe these systems months before the mergers happen and issue warnings with precise estimates of source locations and merger times [35, 40]. Such warnings would be of highest value for electromagnetic and particle observatories to prepare themselves in advance for deep studies of the faint kilonova signals from the very onset of the emission.

Another exciting signal LGWA can observe is a tidal disruption event (TDE) when a main-sequence star or white dwarf plunges into a black hole. Past electromagnetic observations of TDEs were connected to supermassive black holes (for example [41]), but they are also predicted to occur at intermediate-mass black holes (IMBHs), which makes them detectable by LGWA [42, 43]. The elusive nature of IMBHs makes the observation of TDEs a very interesting additional channel to infer properties of the IMBH population and their local environments.

TECHNICAL OVERVIEW

The inertial sensor developed for LGWA must be able to detect fm/$\sqrt{\text{Hz}}$ motion in the decihertz region in a cryogenic environment. The baseline design adopted for LGWA is a monolithic mechanical structure made of niobium in the form of a Watt's linkage with interferometric readout. A previous version made of aluminum with an interferometric readout developed at Nikhef between 2014–2018 is show in figure 5. For the Nikhef Watt's linkage, a sensitivity of several fm/$\sqrt{\text{Hz}}$ was demonstrated down to 30 Hz [12]. The observed excess noise below 30 Hz was due to residual motion of the test platform.

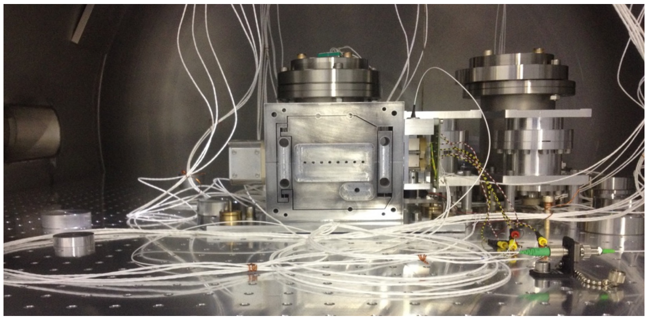

FIG. 5. Photograph of the Nikhef room temperature monolithic accelerometer with an interferometric readout. The sensor is operated in force feedback mode using a coil-magnet actuator.

A new funded proposal for a cryogenic superconducting inertial sensor (CSIS) [44] aims to demonstrate a fm/$\sqrt{\text{Hz}}$ sensitivity down 1 Hz. In figure 6 a schematic overview of the sensor is shown. The sensor self-noise features a fifty-fold reduction of thermal suspension noise over the previous design by operating in deep cryogenic temperatures < 10 K, by increasing the mechanical quality factor, and by implementing a new proof-mass actuation system [12].

Two thin film spiral coils in combination with the flat surface of the proof mass – the orange rectangles in figure 6 – act as actuators. At cryogenic temperatures, the superconducting coils exert a magnetic pressure on the superconducting proof-mass surface by the Meissner effect. Because they are push actuators only, two per inertial sensor are needed. The absence of magnets ensures that dissipation in the system is dominated by structural damping projected to reach a quality factor of $Q = 10^4$ with a 0.1 Hz resonance. At low frequencies, the CSIS sensitivity is thermal-noise limited and with the fm/$\sqrt{\text{Hz}}$ interferometric readout, inertial displacement sensitivities shown in figure 7 are obtained.

Currently, the CSIS niobium sensor mechanics are

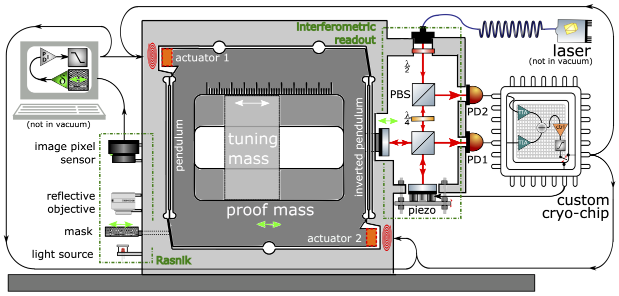

FIG. 6. A cryogenic superconducting monolithic inertial sensor. An interferometric readout provides an error signal containing information on the position of the proof mass. The proof mass is suspended from the frame by a regular pendulum and inverted pendulum. This is known as a Watt's linkage and allows for an arbitrarily low natural frequency, increasing the mechanical sensitivity. The error signal is fed to the actuators to lock the mass with respect to the frame and is used as sensor output. Another loop, using a Rasnik [45] as long-range sensor, damps the resonance peak, reducing proof mass motion such that the other readout can work with high precision over a short range. The custom cryo-chip is under development using CMOS technology.

being fabricated and a table-top version of the novel polarized interferometric readout is being characterized [46]. Progress with the superconducting actuators is summarized in ref. [47]. Full performance tests of such ultra-sensitive inertial sensors below a few Hertz have been limited in the past by seismic background noise, which lies several orders of magnitude above the fm/$\sqrt{\text{Hz}}$ readout noise in the decihertz band. Accordingly, conclusive performance demonstrations of LGWA sensors require new test facilities (see below).

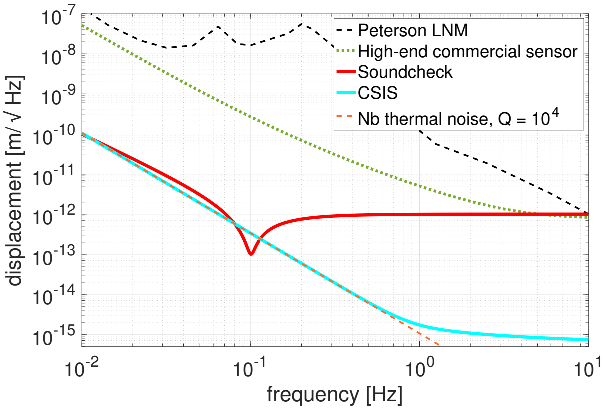

FIG. 7. Comparison between the Peterson low noise model (LNM) [48] and minimum detectable inertial displacement for a high-end commercial seismometer [49] and the proposed CSIS. The currently investigated niobium sensor can achieve a thousand-fold improvement around 1 Hz. The Soundcheck concept with its Rasnik readout [45] achieves 10^{-12} m/$\sqrt{\text{Hz}}$ sensitivity down to 0.1 Hz.

Alternative designs of sensors operating above 5 K are possible. e.g., by substituting niobium in the actuator with high critical temperature (T_c) superconductors. Silicon is a potential alternative material for a cryogenic Watt's linkage, which would improve the performance of the inertial sensor below the decihertz band, but it comes at the cost of increased complexity of the mechanics manufacturing. For deployments outside the cryogenic environment of PSRs, niobium could be replaced by other metals or fused silica as material of the Watt's linkage.

LGWA cryocooler: At zero-field, a temperature of around 9 K would be sufficient to be in a full Meissner state but in order to account for actuator field and to have a margin against, e.g., temperature fluctuations, we chose to aim at an operating temperature of 5 K . Given the temperatures found in PSRs, an additional cryogenic system is necessary. Starting from a 30–40 K environment of the PSR, the 5 K thermal reservoir will be provided by low-vibration sorption cooling technology [50, 51]. In a sorption cooler, such low temperature is established in two steps. First, a sorption cooler operating with hydrogen gas realizes a temperature of about 15 K. A second sorption cooler operating with helium gas is precooled by this hydrogen stage, and is able to reach 5 K. Both coolers have two-stage compressors and cooling is obtained via the Joule-Thomson effect. Heat will be removed from the system by radiator panels. Sorption coolers have no moving parts, apart from some passive check valves, which leads to a very long expected lifetime. In contrast to mechanical piston compressors, a very low level of vibrations is generated. Finally, the absence of moving parts permits scaling of the cooler to small size.

LGWA Soundcheck: Its inertial sensor design will adopt most of the components of the ultimate LGWA sensor design and be compatible with the natural cryogenic environment of a PSR, but it will not implement a cryocooler. It will obtain pm/$\sqrt{\text{Hz}}$ sensitivity down to 0.1 Hz, which exceeds the performance of high-end terrestrial seismometers (see figure 7) and of any of the planned lunar sensors (e.g., part of the Farside Seismic Suite and the Lunar Geophysical Network) by more than an order of magnitude in the decihertz band.

LGWA test facilities: Once the prototyping of the LGWA payload commences, characterization facilities are necessary to prove the extreme sensitivity of the inertial sensors, both for LGWA Soundcheck and the final LGWA payload. The technology of inertial platforms has experienced a rapid development in the past decade, since they are key elements of seismic isolation systems of current and future GW detectors on Earth [52, 53]. While it is beyond our technological abilities to emulate the extremely quiet lunar seismic environment on Earth in the decihertz band, it is possible to get within 2–3 orders of magnitude to the expected lunar seismic background noise by realizing an in-vacuum inertial platform with an advanced active seismic isolation constructed in a quiet underground laboratory. Such a facility is under planning at the National Laboratories of Gran Sasso for cryogenic payloads. The rejection of the last 2–3 orders of magnitude of platform vibrations to get to the level of the lunar seismic background will be achieved by a huddle test, i.e., an optimized subtraction of signals between two sensors deployed side-by-side on the platform.

For LGWA Soundcheck, a demonstration of its $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ sensitivity in the decihertz band can be achieved at facilities already under development like the room-temperature facility SILENT [54], and the cryogenic facility E-TEST [55].

LUNAR SCIENCE AND EXPLORATION

As an ultra-sensitive monitoring system of lunar surface vibrations, LGWA is tightly linked to lunar science and exploration. LGWA mission planning requires an understanding of the Moon's internal structure and seismic background. The Moon's internal structure is the best understood among extraterrestrial planetary bodies, due to the large amount of data collected by ground-based and space-borne geodetic observations or by instruments deployed on the lunar surface. Measurements of tidal deformation or physical librations carried out by means of lunar laser ranging, gravimetric and altimetric techniques are intrinsically sensitive to large scales and the deep interior structure [56]. In addition, the Moon and Mars are the only extraterrestrial bodies for which seismic data are available. Instrumentation deployed by the ALSEP (Apollo Lunar Surface Experiments Package) project [57] provided seismic data that led to the observation and characterization of moonquakes and meteoroid impacts [58, 59] and to a suite of progressively refined velocity models for the lunar interior [60–62]. While there is still no consensus on a reference Moon interior structure, available models allow us to provide sufficiently accurate estimates of the lunar GW response and therefore of LGWA's sensitivity.

Despite the large amount of available data, the Moon's internal structure is not completely unveiled. Most notably, current observational constraints are consistent with both a uniform fluid core and with a differentiated structure assuming an inner solid core surrounded by a fluid outer layer [61]. From a different perspective, gravity data from GRAIL (Gravity Recovery and Interior Laboratory) mission [63] has been used to construct a high resolution spherical harmonic model that evidenced previously unresolved structures like tectonic structures, volcanic edifices and craters.

LGWA can be seen as the result of a natural development from pure lunar geophysical missions to a mission that can see astrophysical and cosmological signals [28]. The Farside Seismic Suite (FSS) will be deployed in the Schrödinger basin on the Moon with an approved CLPS-PRISM mission (expected to launch in 2024/2025) adopting the sensor design of the Mars InSight mission [19]. Since the FSS seismometer will have greatly improved sensitivity over the Apollo seismometers, we can expect new insight into the distribution of weak seismic disturbances to the benefit of LGWA. The Lunar Geophysical Network (LGN) was proposed consisting of 4 separate deployments on the Moon [64]. In addition to the invaluable information it would provide about the Moon, this mission is of great interest to LGWA since station deployment and lifetime have similar requirements to LGWA (albeit, LGN deployments are not proposed inside PSRs).

LGWA will contribute to and improve the catalogue of moonquakes by reducing the event detection threshold and extending to lower magnitude events. These new data together with the use of modern machine-learning methods [65] will contribute to the next generation of Moon interior models. Finally, the assessment of regolith properties [66] would also benefit from the correlation analysis of seismic noise recorded by LGWA's small-aperture array of inertial sensors.

COST AND SCHEDULE

The grass-root cost estimate for LGWA Soundcheck, which does not require a deployment by rover and with a relatively short targeted lifetime, is compatible with the CLPS-PRISM program (US\$30M). The full LGWA mission cost in addition to the sensor cost has to include launch, deployment of fours stations with a rover, optical fiber, power supply to survive 10 years inside a PSR, operation and communication. However, this cost depends on the trade-off/leverage for the type of deployments and power utilized with the progress of the facilities that will be made available through the Artemis program. With these caveats, the full mission estimated cost is in excess of US\$500M pending to complete a design lab.

- 2025: TRL6 LGWA Soundcheck inertial sensor with $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ sensitivity in the decihertz band. Schedule is driven by completion of LGWA test facility, in-vacuum test platform to emulate 40 K environment, expected in 2024. A proposal to CLPS-PRISM program type could be submitted as early as 2025.

- 2029: TRL6 LGWA cryogenic inertial sensor with demonstrated sub-$\mathrm{pm}/\sqrt{\mathrm{Hz}}$ sensitivity above 0.1 Hz and $\mathrm{fm}/\sqrt{\mathrm{Hz}}$ sensitivity above 1 Hz. Complete design lab of the entire mission concept. Schedule includes completion of LGWA test facility, development of readout system for inertial sensor, definition and test of the additional hardware and data analysis techniques. Assuming selection from a program supporting large missions within this decade, a deployment in early 2030 is conceivable.

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