LIGO Voyager

White Paper for MPSAC committee on Next Generation GW Observatories

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June 12, 2023

1 Introduction

The current LIGO detectors will approach the thermodynamic and quantum mechanical limits of their designs within a few years. Over the past few and next several years, Advanced LIGO (aLIGO) is undergoing an upgrade, designated "A+". The chief aims of that upgrade are to lower the quantum (shot) noise, through the use of squeezed light, and to reduce the thermal noise from the mirror coatings. That upgrade has the goal of enhancing the sensitivity by ~50% [1].

The concept discussed in this proposal [1], **Voyager** [2], represents a more substantial upgrade that would increase the range by a factor of 4 – 5 over aLIGO, and the event rate by approximately 100×, to more than one detection per hour. With a Voyager upgrade we expect several BNS mergers and around 50 BBH mergers per day. This upgraded instrument will be able to detect binary black hole mergers out to a redshift of 7.

Fundamentally, the upgrade uses new materials and technologies to lower the detector noise floor. The amorphous silica glass mirrors of LIGO are replaced with crystalline silicon, operated cryogenically near 120 K. The switch to cryogenic silicon optics dramatically improves the power-handling capability of the interferometer, lowering the quantum noise limits. The use of cryogenic thin-films lowers the thermal noise of the mirrors by at least a factor of 5.

1.1 Compatibility with other proposals

There is significant ongoing research in the field of gravitational wave detector technology. Much of the current focus is on researching improvements through new coatings and higher operating power with current fused silica mirrors [3]. Thermal distortions in silica are increasingly problematic in LIGO and Virgo. Without significant improvements in the adaptive optics that are meant to compensate these effects, the LIGO sensitivity will not

[1] This white paper has the internal document number LIGO-M2300123.

be able to increase much beyond the A+ level. As described in [3], the R&D on room temperature coatings and high power adaptive optics must both be successful in the next several years in order to achieve the ambitious sensitivity goals of the post A+ upgrade (the so-called A# upgrade). Until these technologies demonstrate they can meet the demanding requirements, significant risk remains in the room temperature approach.

The Voyager upgrade is primarily aimed at reducing these two major risks. The concepts presented in this proposal look to use **alternative materials** (amorphous silicon coatings and silicon test masses) and technologies (cryogenics) that are, as much as possible, **compatible** and **complementary** with existing 3$^{\text{rd}}$ generation detector research.

2 Astrophysical Science Targets

The first detection of gravitational waves (GWs) from the object GW150914 [4] inaugurated a new field of study: gravitational wave astronomy. The subsequent detection of a binary neutron star (BNS) merger [5] initiated the field of multi-messenger astronomy, including gravitational messengers.

The Voyager upgrade, described in this document, provides a dramatic increase in the sensitivity of the detectors, increases the precision of existing measurements, vastly increases the event rate, and enables GW detection at cosmological distances for the first time.

The improvement in astrophysical science return for Voyager-like detector improvements is covered in [6]. Briefly:

Binary mergers at cosmological distances will be observable with LIGO Voyager. For neutron star binaries, the maximum redshift at which mergers can be detected approaches $z \approx 0.5$, rising to $z \approx 7$ for black hole binaries (BBH) with $30\,\mathrm{M}_\odot$ components. Hundreds or thousands of detections will allow us to precisely characterize the long-sought NS equation of state (EOS) [7] and NS and BH mass and spin distributions in merging binaries.

The evidence for **the existence of intermediate-mass black holes** (IMBHs) in the 10^2 – $10^4\,\mathrm{M}_\odot$ mass range is still inconclusive at present. Attempts to look for electromagnetic signatures are hampered by the small dynamical footprint of low-mass IMBHs and the difficulty of associating phenomena such as ultraluminous x-ray sources specifically with IMBHs [8]. On the other hand, a handful of promising sources have been observed [9], and multiple formation scenarios have been proposed—though none without problems (see the introduction of [10] for a brief review). Thus, GW observations of compact objects in this mass range, which would be enabled by a future detector with good low-frequency sensitivity, could yield the first definitive proof of IMBH existence at the low end of the IMBH mass range [11]. Such measurements could also answer outstanding questions about the dynamics of globular clusters and about the formation history of today's massive black holes [12].

High precision probes of highly curved spacetime [13, 14] will be enabled by the enhanced Voyager sensitivity. LIGO's first observations of GWs from binary black holes have already made it possible to perform the first tests of general relativity (GR) in the highly relativistic strong-field regime [15]. LIGO Voyager instruments will allow us to significantly improve the precision of such tests – some of the binary black hole mergers will have a signal-to-noise ratio of hundreds.

GW memory may be left behind by most stellar collapse events, even those that do not result in an explosion. The typical growth timescale of the memory is of order $\gtrsim 0.1\,\mathrm{s}$, which makes it the only known low-frequency GW emission process in stellar collapse. Detecting the GW memory from a galactic event with aLIGO may be a difficult task even if the full projected low-frequency sensitivity is reached, but the baseline LIGO Voyager design would allow detection.

Measurements of the Hubble Constant will also be aided by the increased broadband sensitivity. Roughly speaking, the uncertainty in the estimate of H_0 scales as $1/\sqrt{N_{\mathrm{BBH}}}$, where N_{BBH} is the number of detected binary black hole mergers [16]. In this approximation, Voyager would reduce the GW based uncertainty in the Hubble Constant by a factor of ~ 2.5 relative to the A+ upgrade of aLIGO. Voyager will enable detection of the *first high redshift GW signals*.

Pre-merger detections of BNS can provide an alert for other observatories up to 1 minute before merger, as described in the LIGO India science study [17]. Pre-merger detections will enable electromagnetic observations of the prompt emission. Early optical and ultraviolet observations will give key insights into the r-process that produces many of the heavy elements on the periodic table. Early observations made in the radio band could indicate pre-merger magnetic reconnection events, and might also be able to shed light on the mechanism of the powerful class of fast radio bursts.

3 Overview of the Voyager Design

The topology of Voyager, illustrated in Fig. 1, is virtually identical to A+ (a dual-recycled Fabry-Perot Michelson interferometer with squeezed light injection). This is by design, to maximally reuse existing components and infrastructure.

- Quantum noise will be reduced by increasing the optical power stored in the interferometers and by reducing the losses experienced by the injected squeezed vacuum.
  - *Optical power*: In aLIGO, the optical gain (Watts/strain) is limited by thermally-induced distortions of the mirror. These effects will be alleviated by choosing a test mass material with a high thermal conductivity, such as silicon.
  - *Squeezing loss*: Cryogenic silicon has little to no thermal expansion, eliminating distortions on the test mass surfaces associated with small angle scattering losses. Additionally, the longer laser wavelength of Voyager reduces large angle scattering losses in the main detector by nearly a factor of 4.
- The test mass temperature will be lowered to 123 K, to mitigate thermo-elastic noise. This species of thermal noise is especially problematic in test masses that are good thermal conductors. Fortunately, in silicon at 123 K, the thermal expansion coefficient crosses zero, which eliminates thermo-elastic noise. (Other plausible material candidates, such as sapphire, require cooling to near 20 K to be free of this noise.)

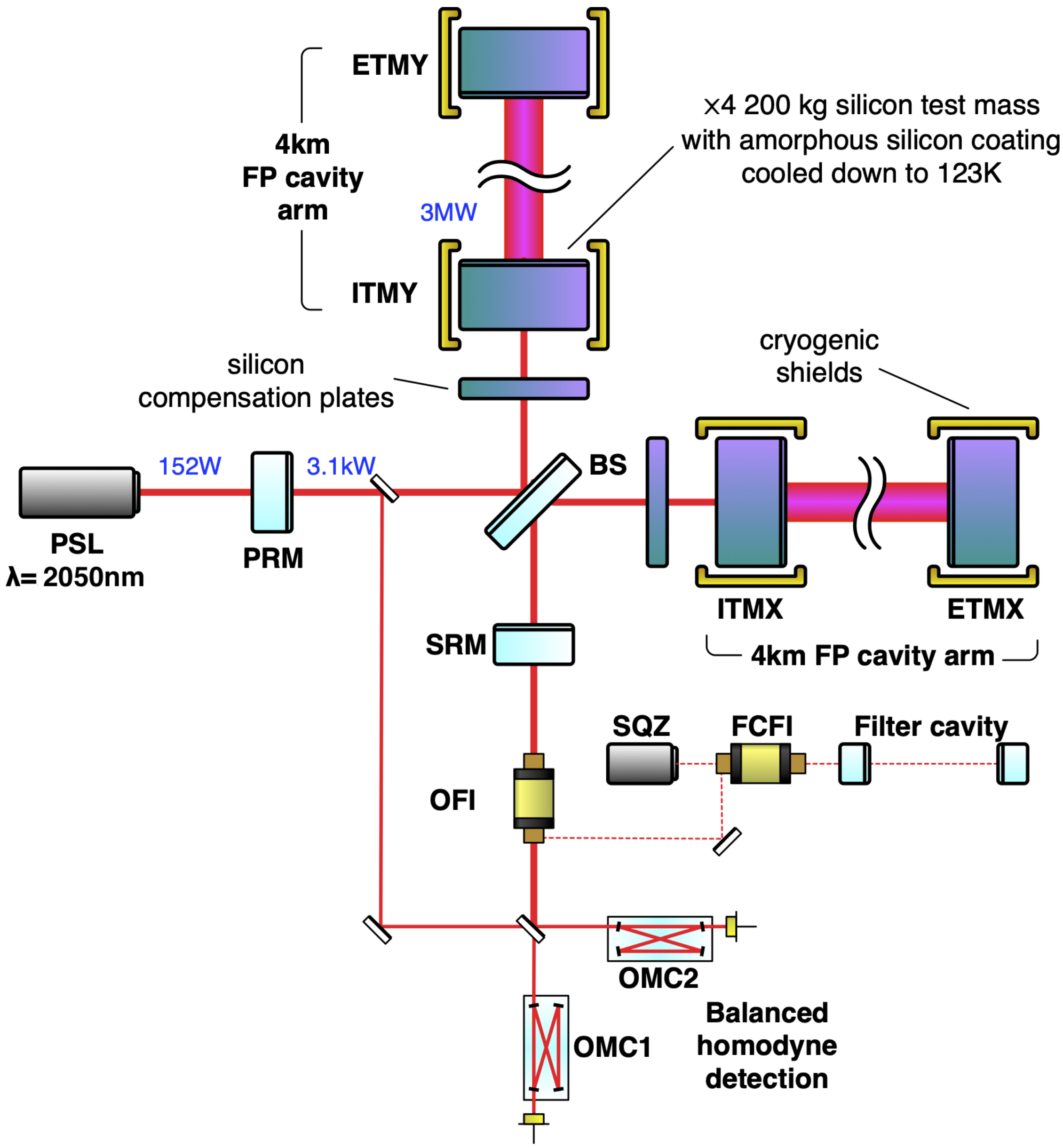

Figure 1: A simplified schematic layout of Voyager: nearly identical to aLIGO. Dual-recycled Fabry-Perot Michelson (DRFPMI) with frequency dependent squeezed light injection. The pre-stabilized laser (PSL) has a wavelength of ~2050 nm. Cold shields surround the input and end test masses in both the X and Y arms (ITMX, ITMY, ETMX and ETMY) to maintain a temperature of 123 K in these optics. The high-reflectivity coatings of the test masses are based on amorphous silicon. Taken from [2].

- The thermal noise of the mirror coating will be reduced by switching to low dissipation amorphous silicon based coatings (in addition to reducing the temperature).

Put together, this cryogenic interferometer design exploits the physical limits of the existing LIGO facilities and maximizes the scientific return on that major investment.

3.1 Overview of Voyager Noise Budget

Using models developed for estimating the noise in aLIGO, we have produced an estimate of the major contributing noise sources for the Voyager Baseline configuration (see Fig. 2). Details of each of the noise processes can be found in [2].

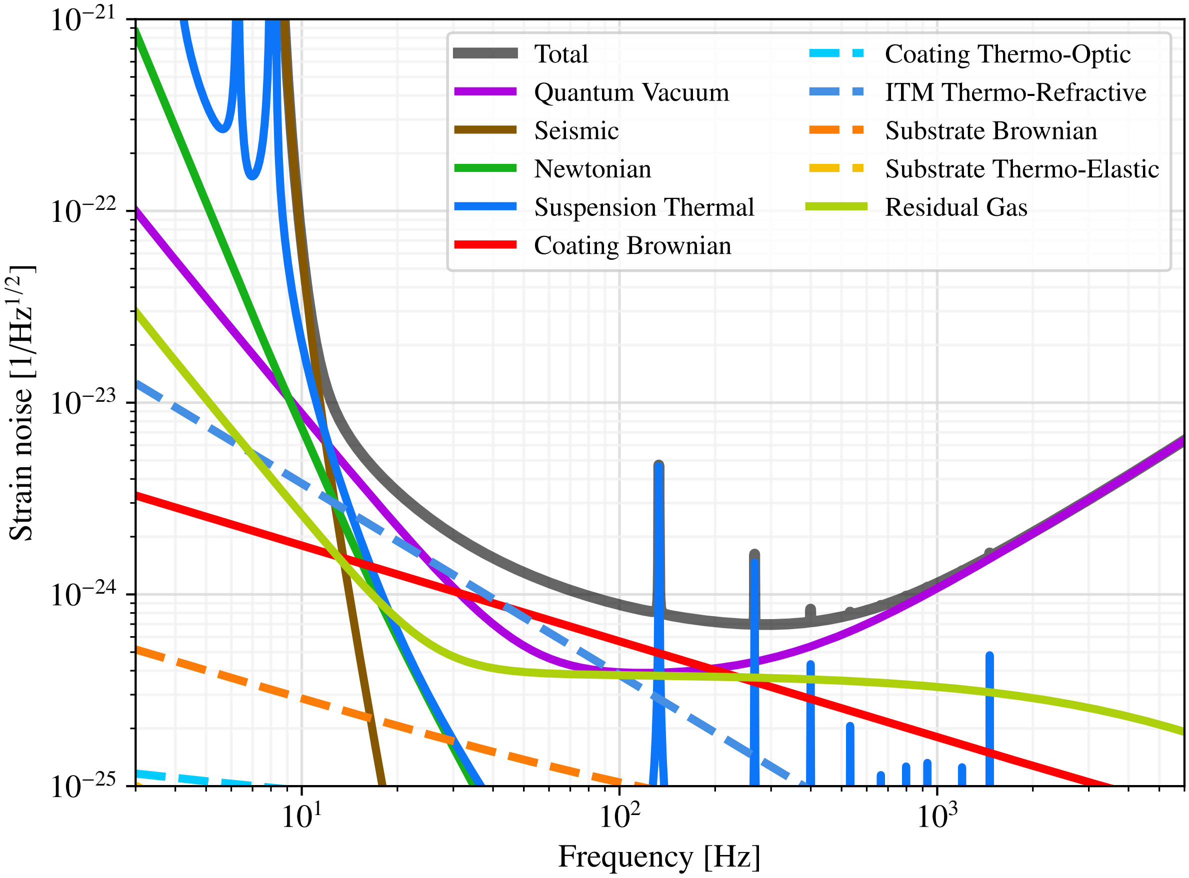

Figure 2: Contribution of technical and fundamental noise terms to the overall Voyager "deep" strain noise spectrum.

The parameters of the Voyager configuration have been tuned to maximize the range for BNS and BBH signals [2].

[2]the Voyager Wideband configuration is optimized to give good SNR for the BNS merger signal near 3 kHz.

In addition to the quantum radiation pressure and shot noise limits, the mirror substrates have a thermo-refractive noise which is driven by temperature fluctuations in the substrate. This noise source is higher in silicon than silica, but is expected to be approximately equal to the other noise sources.

One of the key improvements in Voyager is the use of amorphous silicon dielectric coatings. These are, to date, the only amorphous dielectric coatings with low enough mechanical losses to yield a major reduction in the coating Brownian noise. Coupled with the cryogenic operating temperature, Voyager would give a factor of 5 reduction in the Coating Brownian noise of the detector (red trace in Fig. 2), not possible with the existing dielectric coatings at room temperature.

3.2 Configurations

A family of Voyager configurations has been designed, focusing on "deep" and "wideband" observing scenarios, as well as an "intermediate" configuration that defers certain technical risks. Sensitivity curves for these configurations are shown in Fig. 3.

The "intermediate" configuration is targeted to minimize the R&D needed to prepare for the first Voyager observing run. The size of the ITMs and the beam spot size are decreased, to reduce the risk of procuring large silicon substrates. The HR coatings use proven low absorption materials in the top few layers,[3] to mitigate any excess α-Si absorption. The bottom suspension stage uses metal blade springs in lieu of silicon blades. Seismic motion is assumed to be the same as aLIGO, and Newtonian gravity noise subtraction is moderate. Although the "intermediate" configuration has high noise background below 30 Hz, it would be a good, low–risk alternative to start with.

The "deep" and "wideband" configurations differ from each other only in the signal recycling mirror (SRM) transmittance, and the squeezing filter cavity mirror reflectivities.[4] In the "deep" configuration, the SRM transmittance was optimized for BNS inspiral range. In the "wideband" configuration, it was chosen to optimize sensitivity above 1 kHz.

Both configurations adopt the same arm cavity finesse, chosen as a compromise between mitigating the noise contribution of signal cavity loss at high frequencies, and the contribution of ITM thermo-refractive noise at low frequencies. By optimizing the arm finesse for each observing scenario individually, it would be possible to obtain a further improvement in the sensitivity. However, it would then be necessary to modify the power recycling mirror (PRM) and ITMs, in addition to the SRM and filter cavity, when changing between the configurations.

[3]The thermal noise of this mixed coating is roughly estimated, not modeled in detail.

[4]Our experience in swapping SRM transmittance in aLIGO, was relatively benign, so we expect there to be minimal downtime in re-commissioning the interferometer after such a change.

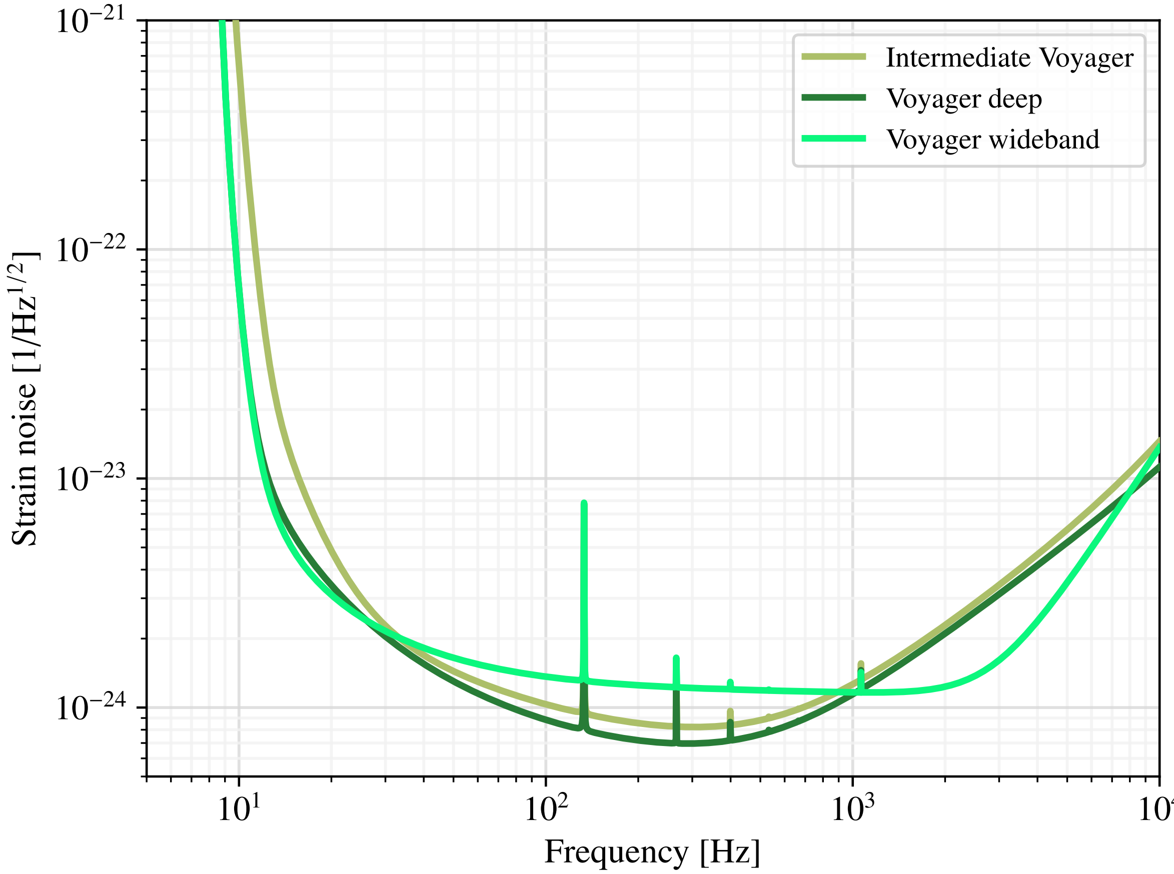

Figure 3: Comparison of the noise of three candidate Voyager configurations: (i) Voyager Baseline (Wideband), (ii) Voyager Deep, (iii) intermediate Voyager. The first two configurations illustrate how the bandwidth of the detector can be adjusted by swapping mirrors with different reflectivities. The intermediate configuration incorporates several design changes (described in Table 1) to mitigate the main risk factors, with a modest reduction in sensitivity. Comparisons of the Voyager Baseline and Voyager Deep curves with other sensitivity curves (A+, A#, etc) are shown in Fig. 6.

4 Technologies Requiring Development

The Voyager upgrade will largely reuse the major aLIGO hardware: the vibration isolation platforms, the main vacuum system, and the existing buildings and facilities.

The major components to be changed include the four silicon test mass mirrors and their quadruple suspensions, a silicon beamsplitter, the main laser system, a cryogenic shield assembly to cool the test masses radiatively, and a replacement of all auxiliary optics to have coatings for a 2 µm wavelength. Most of the mirror suspensions will not be changed. The existing analog and digital control and data acquisition system can be reused in its entirety.

In the text below, we highlight the main technical changes in the Voyager upgrade.

4.1 Silicon test masses and suspensions

The substrates for the 200 kg mirror will be taken from 45 cm diameter monocrystalline silicon boules. Such crystals are grown by the Magnetic Czochralski method, reaching the very high levels of purity needed for use in the semiconductor industry. Small volume samples of this material are currently being inspected to determine if it meets the optical requirements of Voyager.

The reflecting surface of the silicon mirrors will be coated with the layers of low thermal noise materials (see Section 4.3). The noise from Brownian motion of the mirror is further reduced by cooling the mirror. The test mass temperature will be regulated to 123 K, to mitigate thermo-elastic noise. This type of thermal noise is especially problematic in test masses that are good thermal conductors. In silicon at 123 K, the thermal expansion coefficient vanishes, which eliminates thermo-elastic noise.

The silicon mirrors will be suspended on a monolithic silicon suspension by silicon ribbons and vertical blades. Only the lower two stages of the suspension are cooled.

4.2 Cryogenic cooling

Because Voyager's target temperature (123 K) is an intermediate cryogenic temperature, the cryogenic system can be kept relatively simple, using ordinary measures to mitigate stray infrared heating (Fig. 4).

Cooling of the test mass will be radiative, unlike the other detectors that employ conductive cooling. Radiative cooling allows us to omit heat links that could otherwise allow vibrational noise to bypass the suspensions. Also the suspension material and structure can be designed to optimize thermal noise properties, without considering heat transfer capability.

A double-layer cryogenic shield will be used. Only the inner shield needs to be isolated from the ground vibration. Since the outer shield does not see the laser light, it can be directly attached to the chamber wall. The rigid connection allows for enhanced heat conduction from the outer shields to their cryocoolers.

Optionally, radiative cooling can be enhanced by coating the test mass barrel with high emissivity material. Also, interlocking corrugations of the barrel and inner shield can be used to augment the surface area. This technology would further enhance the heat removal from the test masses, thus pushing the circulating power further toward the material limit set by the silicon test mass, which is about 20 times that of silica, and reducing Voyager's quantum noise.

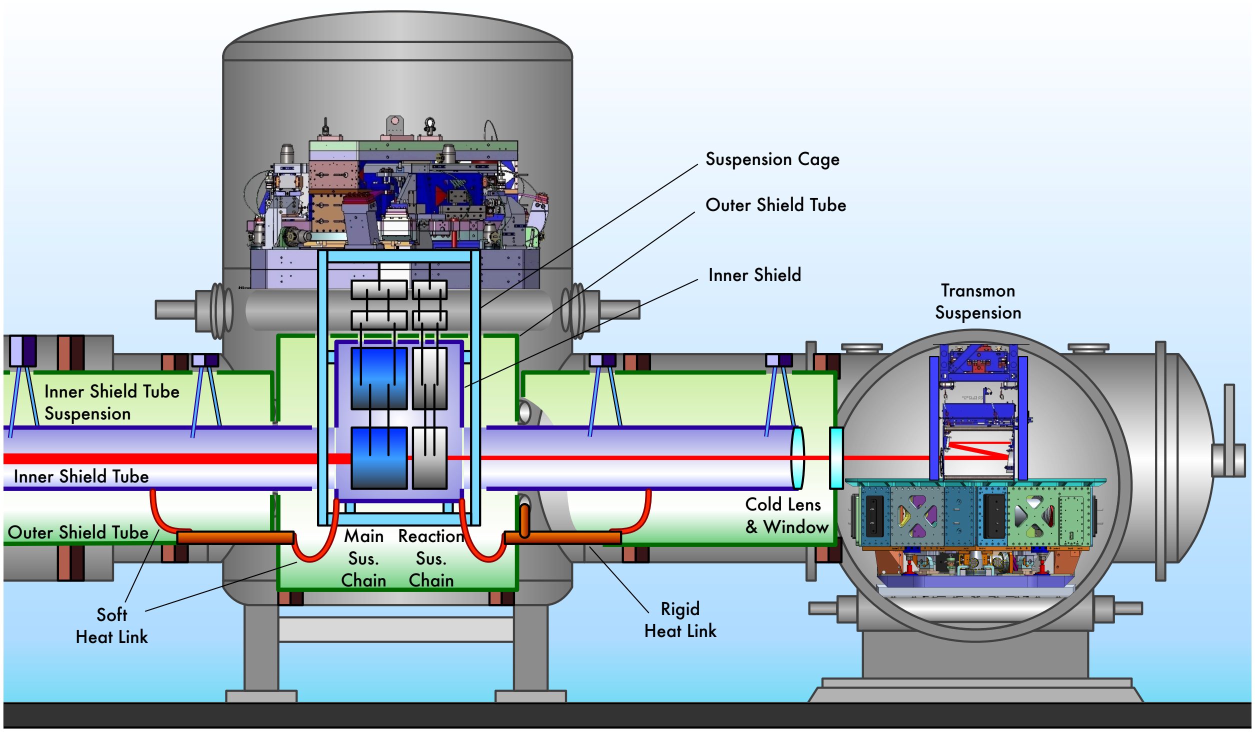

Figure 4: Schematic diagram of the vacuum system and cryogenic shields for an end test mass chamber.

4.3 Mirror Coatings

The current generation of LIGO and Virgo interferometers are limited in the crucial 80 – 400 Hz band by Brownian thermal noise (which stems from internal friction) in the mirror coatings [18]. As of this writing, there is no mirror coating design that can meet the requirements of: (i) ultra-low optical absorption, (ii) low mechanical friction, and (iii) low spatial roughness over the 34 cm mirror diameter. Currently, the LIGO Scientific Collaboration is exploring the use of some candidate amorphous materials for the A+ upgrade, and the possibly use of GaAs:AlGaAs [19] for the A# upgrade [3]. Although the crystalline, GaAs based mirror coatings have shown promising performance in small interferometers, they currently cannot be produced at the required size, and observations of their noise properties at low frequencies [20] present an un–retired risk that needs to be resolved before installing them in a LIGO upgrade.

Reducing the operating temperature from 300 K to 123 K reduces the thermal noise directly ($\propto \sqrt{T}$). However, for most amorphous thin films, the internal friction either stays the same or increases below room temperature. Amorphous silicon, on the other hand, shows a dramatic decline in the internal friction [21] as its temperature is reduced. Recent advances in deposition approaches show steady progress in reducing the optical absorption at 2000 nm. Paired with a low refractive index material such as amorphous silica or silicon nitride [22], the Voyager mirrors should exhibit a thermal noise level at least 5x below that of the current Advanced LIGO mirrors.

Although mirror coatings have been made with these materials, further development is required to produce a high reflectivity mirror stack with demonstrated low absorption and low mechanical loss.

4.4 High Quantum Efficiency Photodetection

Voyager's high frequency sensitivity is achieved with high power operation and substituting unsqueezed vacuum fluctuations with a highly squeezed vacuum state. Any losses in the system provide a path for unsqueezed vacuum to couple to the readout, with small losses significantly degrading the squeezed state. Therefore, the squeezing loss budget is very strict. For the readout photodetectors (PDs), this includes a maximum allowable loss of 1%, implying very high (≥ 99%) quantum efficiency (QE) at the 2 µm operating wavelength.

Direct detection of IR radiation is possible with PIN junction photodetectors made from HgCdTe and InAsSb. The maximum demonstrated QE of these detectors is of the order of 90% and will need improvement for use in Voyager. Extended InGaAs has a relatively low QE (≃ 80%) but is readily available commercially. These are very suitable for the auxiliary photodetectors in Voyager that make up more than 95% of the required photodetectors

4.4.1 Frequency upconversion for photodetection

Sum-frequency generation (SFG) provides an alternative path for high QE photodetection. By mixing a strong (e.g. resonantly enhanced) pump, for example at 1064 nm, the 2 µm fields may be upconverted to 700 nm. After upconversion, traditional InGaAs or Si PDs may be used to achieve ≥ 99% QE. Light upconversion for improved photodetection has been demonstrated and exploited in other applications including imaging [23], environmental monitoring [24], and quantum enhanced sensing [25]. In the case of resonant SFG, even a modest finesse (< 1000) cavity providing optical gain for the pump wavelength may reach a quantum efficiency of ≥ 95% [26, 27]. With further R&D, such upconversion quantum efficiencies may approach ≥ 99.9%, matching external QE values attainable with Si devices [28].

4.5 High Power Laser operating at 2 microns

Voyager will operate at a laser wavelength in the range 1900 – 2100 nm with the current prototype wavelength of 2051 nm. The final wavelength selection will depend both on other Voyager subsystem requirements and also on the development of near-IR and mid-IR lasers over the next several years. There are two rare-earth dopants suitable for direct lasing at 2000 nm: thulium and holmium, which can provide optical amplification in the 1900 nm–2040 nm [29], and 2040 nm–2170 nm [30] bands, respectively. Two basic laser architectures are available: optical fiber [31] and free-space [32] lasers. These architectures are not necessarily incompatible and the final system may contain a low-power free-space master oscillator (MO) followed by some combination of power oscillators and fiber amplifiers. Lasers operating CW in this wavelength range have already been demonstrated with output powers of 65 W [33] and 125 W [34].

Although such promising lasers and amplifiers candidates exist, currently there are no commercial laser that meets all of the design specifications. Therefore, some technology development is required. This was also true when Initial LIGO and aLIGO were in the same stages of development that Voyager is today and is not concerning. We expect mid-IR laser development to follow a similar trajectory to the one seen for 1064 nm lasers in aLIGO. In particular:

- commercial development of lasers within this wavelength range is of growing interest and is largely driven by remote sensing applications (e.g. spectroscopy of different gas species, particularly atmospheric CO_2 and water [35]),
- the frequency, intensity and polarization noise requirements for the main laser are expected to be comparable to the existing noise requirements for the aLIGO lasers with no significant barriers to development.

As with aLIGO, the laser is expected to run continuously without requiring major maintenance for the lifetime of the Voyager project, approximately 5 – 10 years. Development in the near-term is required to demonstrate this level of long-term stability in the laser.

5 Timeline, Costs, and Risks

We have shown that the successful implementation of the Voyager technologies would give a tremendous boost to the astrophysical sensitivity of the LIGO network. Here we describe some of the existing technical risks, the expected timeline, and an approximate construction cost for the upgrade.

5.1 Risks

The main risks/unknowns are in the use of silicon as a mirror material, and the operation at low temperature. These risks can be significantly retired in the lab – scale prototypes.

5.1.1 Silicon Mirror Substrates

For the Voyager mirrors, we require single crystal substrates with low internal friction ($Q \sim 10^8$), low absorption for a 2 µm laser wavelength, and a low number of inclusions in the bulk. Float zone silicon is a natural choice, as it easily meets all of the requirements, but unfortunately, float zone silicon cannot be grown in boules larger than 20 cm. Ultra pure silicon has been grown in up to 45 cm diameters using the Magnetic Czochralski (MCz) method.

At the moment, the silicon industry has not yet accepted 45 cm as the standard wafer size, so the number of vendors is limited. As a backup, we consider 30 cm diameter mirrors for the 'Intermediate Voyager' design.

After acquisition of the mirror, it must be thermally processed in order to trap the residual oxygen via annealing. This process has been demonstrated on cm sized samples, but further modeling and experimentation is required to demonstrate this annealing on a Voyager sized mirror.

5.1.2 Optical Mirror Coatings

A variety of low noise, low absorption coatings are under development by the LIGO Scientific Collaboration. a-Si is being pushed by quantum computing community. AlGaAs coatings, and non-binary coating designs are possible alternatives to the Voyager baseline (the latter enables trading noise against absorption if necessary). If the coating requires annealing after deposition on the silicon substrate, there is a risk that the anneal may degrade the absorption of the substrate.

5.1.3 Operation at a 2050 nm wavelength

All of the current large scale GW detectors use an Nd:YAG laser with a 1064 nm wavelength. This technology is well tested and the community is experienced in its use.

Going to a longer wavelength brings in the technical risks associated with new laser technology, as well as risks in the acquisition of optical and electro-optical components of sufficiently high quality.

In the past decade, 2 micron laser technology has developed considerably, driven by applications such as LIDAR, CO_2 gas sensing, medical applications, materials processing, and free space classical and quantum communications. As a result, it is now possible to purchase 2 micron optics and electro-optics of high quality.

5.1.4 Unexpected phase noise in silicon

The long experience with amorphous fused silica optics in the GW field has validated these mirror materials as excellent for low phase noise interferometry. Silicon is a widely used optical material, however, as of this writing, there have been no demonstrations of low phase noise in silicon optics, at the levels required for Voyager.

In order to mitigate the risk of surprising noise mechanisms, we plan to make a high sensitivity prototype interferometer to empirically validate the silicon. Our current models for free carriers, and thermodynamically driven elastic and refractive fluctuations predict that only thermo-refractive noise is relevant (cf. Fig. 2).

5.1.5 High QE for 2 micron squeezed states

Losses in the readout chain, including at the photodetector, limit the sensitivity to GWs, with squeezed states of light being particularly fragile to such losses. For example, if the nominal 99% photodetector efficiency assumed for Voyager were reduced to 95%, it would reduce Voyager's BNS and BBH range by 4% and 1%, respectively. To mitigate this issue, multiple approaches to maximizing the detection efficiency should be pursued, including development of alternate detector materials, and efficient upconversion of the light prior to photodetection.

5.1.6 Excess noise due to cryogenics

In order to avoid the excess vibrational noise that comes with cryogenics, the Voyager design uses purely blackbody radiation to get the heat out of the Voyager test masses. This is similar, in scope, to the current approach of surrounding the test masses with black glass to trap and diffuse light.

The Voyager design aims to avoid vibrations by using Stirling cryocoolers (the vibrations are focused at multiples of the 60 Hz line frequency and are easy to isolate). Technical improvements in low vibration cryogenic straps over the past decades should make it straightforward to cool the mirrors without inducing much vibration.

5.1.7 Monolithic Silicon Suspensions

To achieve the low thermal noise at 10 – 15 Hz, it will be necessary to construct mirror suspensions with silicon ribbons, and silicon blade springs to provide vertical isolation.

The required material parameters are within what has been measured in the literature, but significant engineering work will be required to construct a monolithic suspension that can support a 200 kg mass at cryogenic temperatures. Unlike other low temperature interferometers, such as KAGRA, the Voyager suspension ribbons are not used to cool the mirror. This greatly simplifies the suspension design and fabrication.

5.1.8 Risk Reduction: Integration Testing

The 40 m prototype interferometer lab at Caltech is being prepared and will play a crucial role in validating and reducing technical risks associated with the new technologies. This prototype, called Mariner, will be as faithful as possible to the Voyager design, with reduced size, laser power, and vibration isolation. The prototype facility can make sensitive noise tests at $\gtrsim 100$ Hz.

In this prototype, significant attention will be given to mitigating risks related to silicon mirrors, 2 µm lasers, and radiative mirror cooling. The silicon-related technologies encompass addressing challenges such as absorption, scattering, birefringence, as well as demonstrating effective polishing and coating techniques. Cryogenic aspects will involve integrating cryocoolers, optimizing the thermal design and isolation of cryoshields, evaluating the emissivity of coatings and silicon, and ensuring accurate thermal modeling of the test mass and its immediate environment. Additionally, the prototype will focus on preventing the formation of ice layers on mirror surfaces.

Mariner will serve as a platform to demonstrate stabilization and optical detection techniques specifically for 2 µm laser devices, through the operation of the interferometer.

It is worth noting that a separate endeavor will be undertaken to realize a suspension prototype featuring a full-size silicon mirror.

5.2 Timelines

Voyager represents a project upgrade approximately 40%-50%[5] the size of aLIGO. Therefore, we use the development and installation of that project as a basis to extrapolate the timeline for Voyager. The result is shown in Fig. 5. We anticipate an accelerated installation, compared to aLIGO, as Voyager will re-use much of the aLIGO and A+ infrastructure.

5.3 Approximate Cost

A preliminary construction cost estimate, extrapolated from the actual costs of the aLIGO construction, put the cost for upgrading the two LIGO sites in the U.S. just above the lower limit for Major Research Equipment and Facilities Construction (MREFC) projects. The reason for the large cost savings relative to aLIGO is the re-use of the most expensive components: the in-vacuum seismic isolation platforms, the majority of the mirror suspensions, the analog electronics, and the data acquisition system.

6 Synergies with Multi-Messenger Facilities

The synergies described here are both on the instrumental side (with other GW observatories) and the astrophysics side (with both GW and EM facilities).

6.1 Synergy with other gravitational wave detectors

The forthcoming direction of laser interferometer gravitational wave detection is to build detectors with giant and/or cryogenic mirrors. Voyager is a precursor to such third-generation detectors.

[5] $205M for aLIGO in 2008 represents approximately $290M in 2023 (adjusted for inflation)

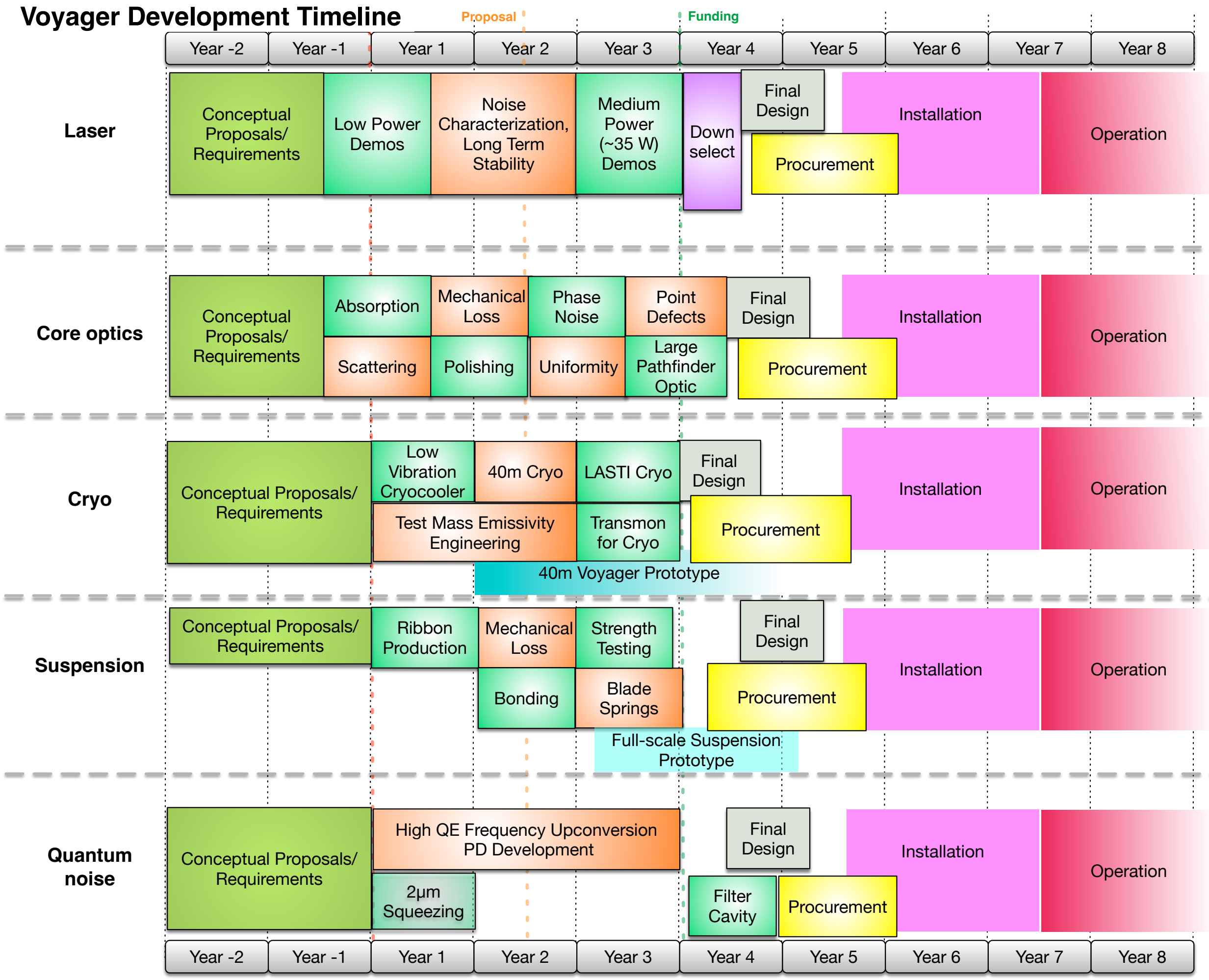

Figure 5: Timeline of Voyager upgrades

The next larger scale GW facilities, Cosmic Explorer (CE) [36] and Einstein Telescope (ET) [37], are expected to begin construction sometime into the next decade, and will usher in a new era of GW astronomy. In the meantime, there will be a need for evolved multi-messenger observations with, for example, the first generation of space-based gravitational wave detectors and coordination with other rapid-response electromagnetic observatories. Voyager can help address this gap by increasing the sensitivity of the existing LIGO observatories.

While Voyager can utilize technology developed for ET and CE, the technological advances resulting from Voyager commissioning will ultimately serve to accelerate the ET and CE construction and operation.

To maintain the significance of the LIGO observatories after ET and CE become operational, maintaining Voyager and its successor detectors will be necessary to maintain a stable era of multi-observatory GW observation.

6.2 Synergy with EM and other observatories

The success of the LIGO and Virgo observatories in detecting the neutron star binary merger GW170814 and its EM follow-up has had an immeasurable impact on the field of astronomy. The future plans of almost all ground-based and space-based observatories featured in Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020) [38] included ToO (Target of Opportunity) EM follow up of GW events as their scientific goals.

Large-scale observatories are being planned to be online in the 2030s. NASA plans to bring a number of multi-wavelength space missions ranging from far IR to X-rays, such as Nancy Grace Roman Space Telescope, NASA's Great Observatories Mission and Technology Maturation Program (HabEx, LUVOIR, Origins Space Telescope, and Lynx). ESA plans to launch Athena X-ray observatory. On the ground, the Vera C. Rubin Observatory (aka LSST) will soon begin operations and will continue to produce results in the 2030s. The US ELT projects (GMT/TMT) will begin operating along with ESO's ELT. In the radio domain, CMB-S4, DSA-2000, and ngVLA should begin observing along with SKA and the existing ALMA. In addition, IceCube-Gen2 will start observing cosmic neutrinos.

In such a situation w,here multi-messenger observations are expected to play an increasingly important role in time-domain astronomy, it will be very crucial to fill the gap between the currently-ongoing LIGO projects and the third-generation interferometers observations from updated gravitational wave detectors such as Voyager.

7 Conclusion

We have described an upgrade of the LIGO interferometers that can utilize the existing facilities, increase the current LIGO sensitivity (circa 2023) by a factor of 4, and thereby vastly improve the detection rate and the cosmological reach ($z \sim 8$) of gravitational wave astronomy.

Unless significant improvement is made in the control of thermal distortions and instabilities, the current LIGO technology (room-temperature fused silica mirrors, having a low thermal conductivity) may be not be sufficient to achieve much higher sensitivities.

The use of cryogenic silicon mirrors in Voyager mitigates the main issues with high laser power that reduce the sensitivity and stability of the current generation detectors (aLIGO and Advanced Virgo).

The Voyager concept includes its own set of risks and technologies to demonstrate. In order to be ready with such an upgrade near the end of the decade it is important to invest now in significant R&D and prototyping efforts to ensure the vibrant growth of this field over the next 20 years.

A Detector parameters

Parameter	Units	iVoy	VoyD	VoyW
Arm power	kW	3000	4000	4000
Laser wavelength	µm	2	2	2
Test mass material		Silicon	Silicon	Silicon
Temperature	K	123	123	123
Test Mass	kg	200	200	200
Total susp. mass	kg	520	520	520
Final stage susp. length	cm	80	80	80
Total susp. length	m	1.6	1.6	1.6
Observed squeezing	dB	9	9	9
Rayleigh wave suppression	dB	6	20	20
Test Mass Coatings		Ta/aSi/SiO_2	aSi	aSi
Horiz. susp. pt. at 1 Hz	$\mathrm{pm}/\sqrt{\mathrm{Hz}}$	10	0.1	0.1
Final susp. stage blade		Aluminum	Silicon	Silicon
ETM beam radius	cm	8.0	8.4	8.4
ITM beam radius	cm	5.2	5.9	5.9
Cavity stability (g-factor)		0.62	0.73	0.73
Transverse mode spacing	kHz	29.6	31.0	31.0
Filter cavity linewidth	Hz	28	36	13
Arm finesse		3100	2000	2000
SRM transmission	%	4.6	9.2	1.1
Arm length	m	3995	3995	3995
Filter cavity length	m	300	300	300
Signal Cavity length	m	55	55	55
RT arm cavity loss	ppm	20	20	20
RT filter cavity loss	ppm	10	10	10
RT Signal Cavity loss	ppm	500	500	500
Exc. gas damp.		2.5	2.5	2.5
Diffusion time	µs	1400	1400	1400

Table 1: Defining parameters of detectors (a-Si: amorphous silicon; RT: round trip). iVoy: intermediate Voyager, VoyD: Voyager Deep, VoyW: Voyager Wideband

B Interferometer sensitivity curves

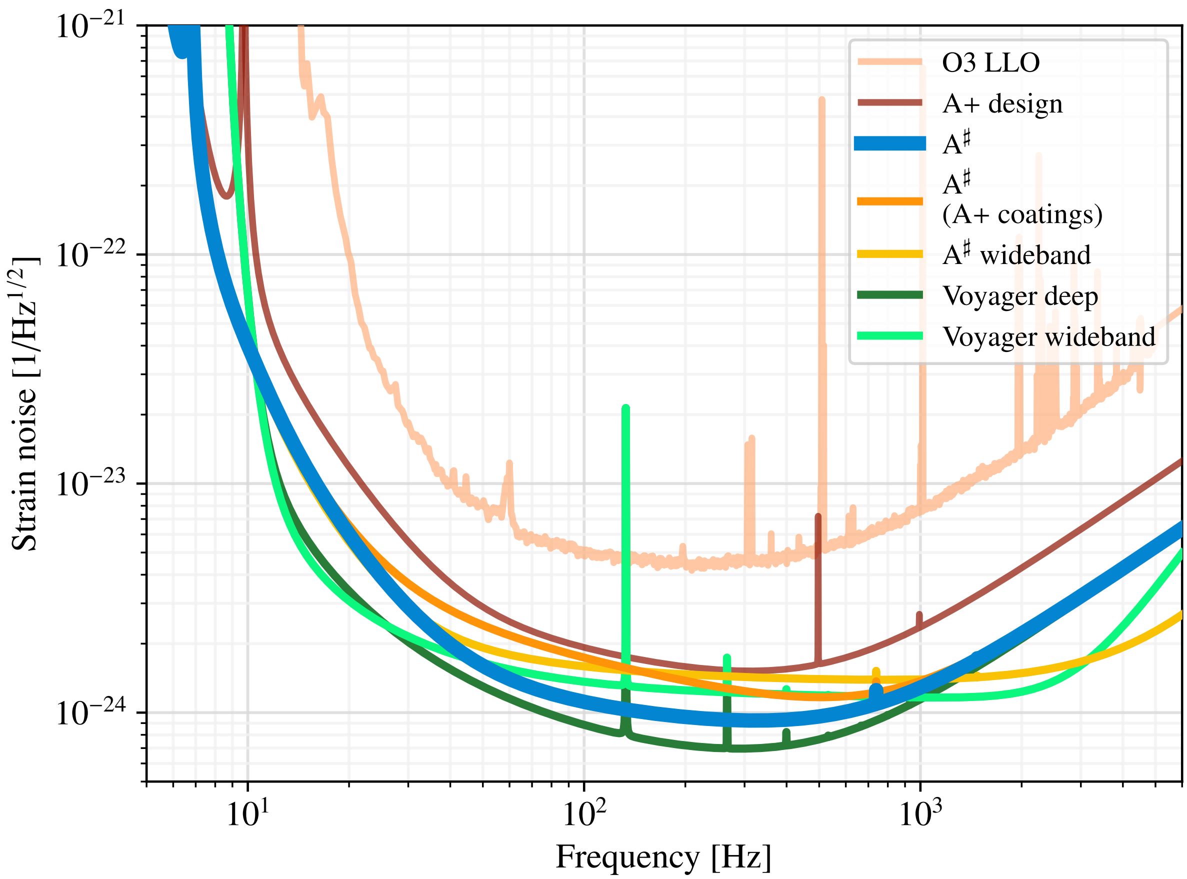

Figure 6: For reference: Comparison of the noise of different gravitational wave detectors and concepts, taken from [3].

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