A Roadmap for the LIGO Observatories in the Era of Cosmic Explorer

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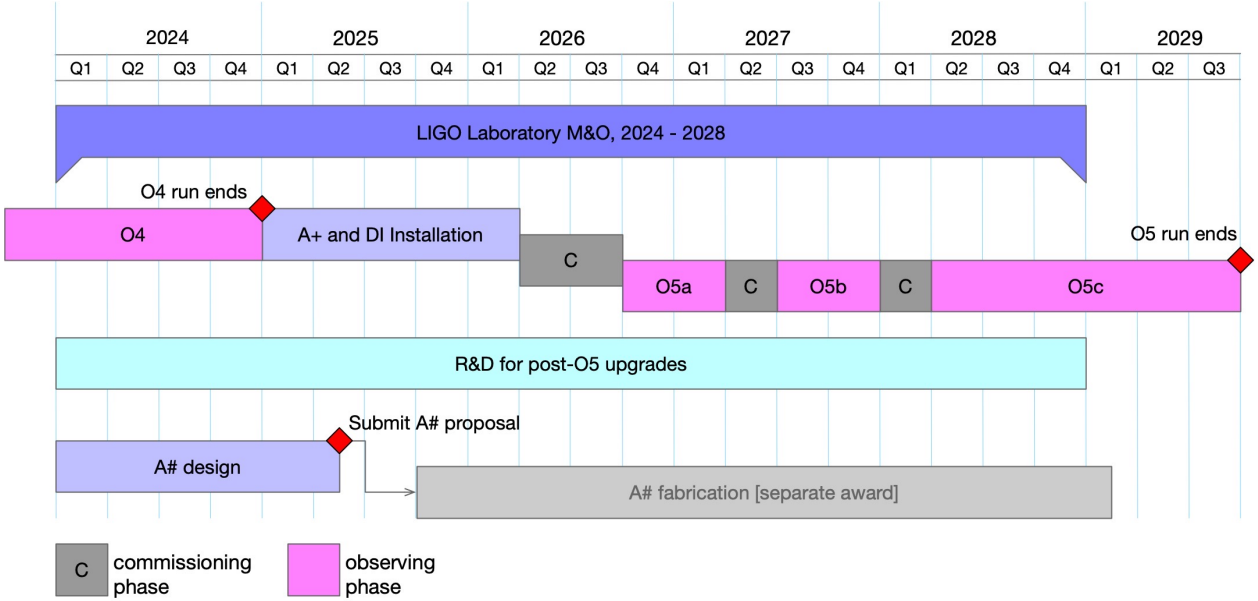
June 7, 2023

Roadmap

- NSF's LIGO Laboratory, operated by Caltech and MIT, has developed a vision for the continued improvement of the detectors housed at the two LIGO Observatory sites for the next 20+ years, consisting of:
  - LIGO's observing and upgrade plans for the LIGO Observatories through 2029.
  - The LIGO detector upgrade program beyond 2029.
  - The synergistic role the LIGO detector upgrade program will play in developing key technologies for the Cosmic Explorer (CE) detector.
  - The International Gravitational Wave Network (IGWN), emphasizing the LIGO Aundha Observatory (LAO) to be constructed in India during the remainder of the decade and operated as part of the LIGO Observatories in the 2030s.
  - Continued investments in upkeep/maintenance of the LIGO Hanford (LHO) and Livingston (LLO) observatories.

LIGO Laboratory Plans Through 2029

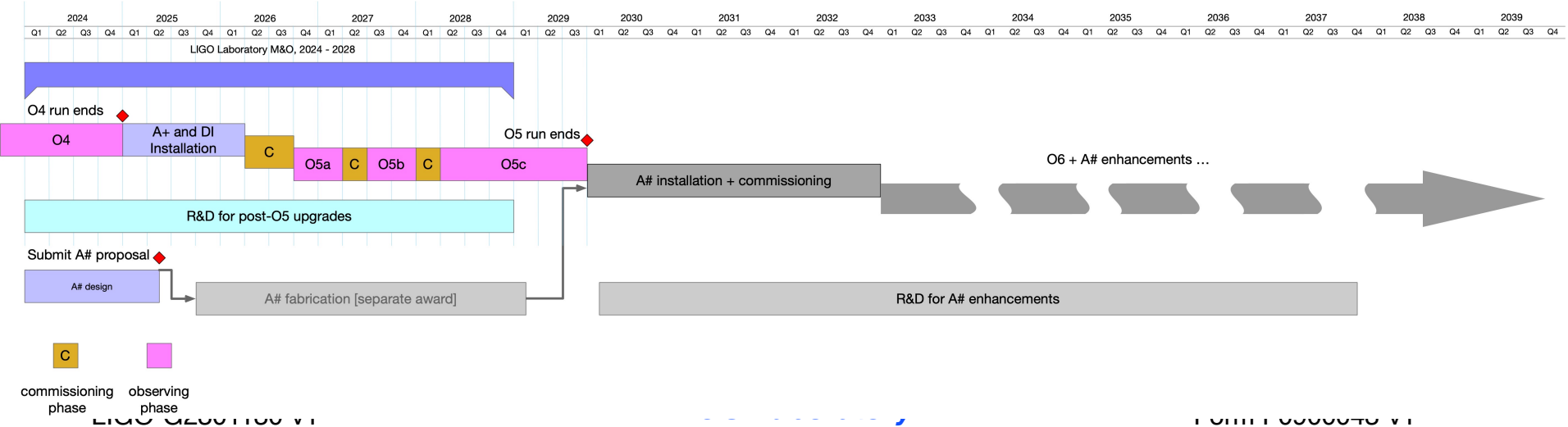
- We have well-defined plans for carrying out observing runs and detector upgrades through 2029*
  - » O4 has started! Two LIGO detectors and KAGRA are running; Virgo making repairs on mirrors; they expect to join in the Fall.
  - » A schedule for completion of the A+ upgrade program period and the O5 observing run has been established.



* NSF may choose to compete the management of LIGO Laboratory for post-2028 operations

LIGO Detector Upgrade Program Beyond 2029

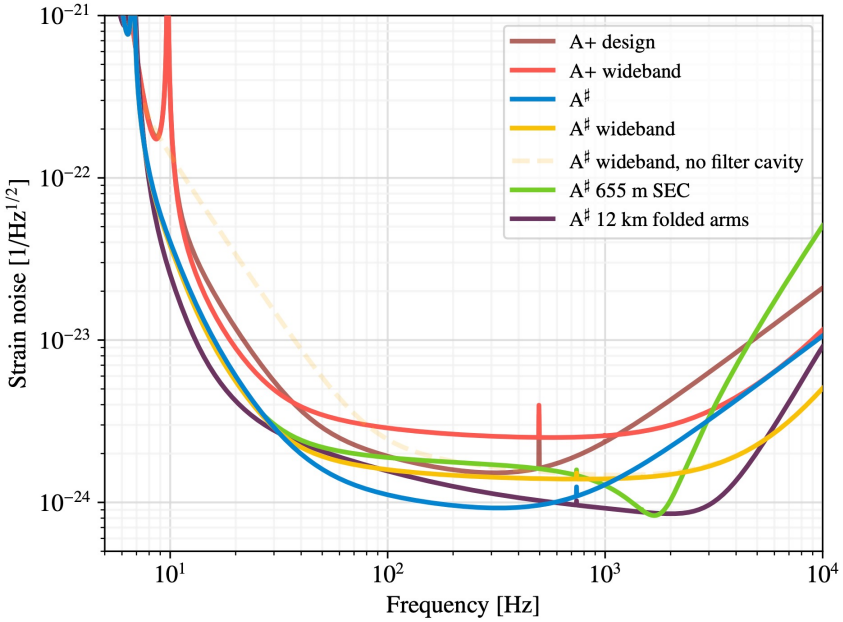
- In 2021, the LSC organized a study group to explore and evaluate upgrades to the LIGO detectors that could be implemented after O5, and the science that could be achieved with more sensitive instruments.
  - LSC White Paper presenting detector design options and science case: Post-O5 Study Group Report
- The Post-O5 report recommends a set of detector improvements—collectively known as A# —that would produce close to a factor of 2 improved strain sensitivity over the A+ design target across the LIGO frequency band.
- *Key point: It is difficult to see a path to achieve more than ~ 2X given 4 km arm length constraint.*



LIGO A# Upgrade Program

- A# design includes improvements across the entire LIGO frequency band from 10 Hz to 5 kHz
  - Low frequency (< 50 Hz): sensitivity improvements from larger test masses, upgraded test mass suspensions, and improved seismic isolation
  - Mid-band (50 Hz to 300 Hz): reduction of mirror coating thermal noise through improved low noise coatings
    - This is the technically riskiest component of A#
  - High frequency (> 300 Hz): higher laser power, reduced quantum noise from increased squeezing
    - Also improves noise below 300 Hz (frequency-dependent squeezing)
    - This is also a risk element in the design
  - Voyager 2 μm, cold silicon technology is an alternative, but not as well developed
- Upgrades are motivated by the science case for A# in the LSC Post-O5 report.
- A detailed design and costing for A# will occur in the 2024-25 timeframe.
  - We are confident that A# will fit within NSF's Mid-scale Research Infrastructure II budget cap (< $100M)

Comparison of Design Options for A#



LIGO as a Technology Pathfinder for the Next Generation of Detectors

- The technology development program for A# is highly synergistic with the technologies planned for CE, building on the successful Advance LIGO/A+ designs.

→ A# will reduce several technical risks in the CE design

Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian suppression	0 db	6 db	20 db

The International Gravitational Wave Network (IGWN) into the 2030s & LIGO-India

- The global ground-based GW collaborations are in the process of establishing the International Gravitational Wave Network
  - Will initially comprise the LIGO, Virgo, and KAGRA detectors
  - Virgo has developed plans for Virgo_nEXT (in parallel to A# on a similar timescale)
- The construction of LAO, a new observatory site by the LIGO-India Project, funded by the India, is ramping up and will utilize the existing components of a third Advanced LIGO detector.
  - Construction period: now through April 2030. Site has been acquired and construction has begun.
  - LAO is currently planned to come online in a configuration similar to the A+ upgrade
- The scientific impact of operating three LIGO detectors of comparable sensitivity on a very long baseline will greatly expand the contributions to multi-messenger astronomy.

LIGO Laboratory Operations into the Era of Cosmic Explorer

- The LIGO Observatories were constructed in 1996-1999 with a planned 25 year operational lifetime
- The past 25 years have seen ‘wear and tear’ on LHO and LLO
  - Particularly the LLO vacuum system in the humid southeastern US, but also hurricanes and floods (LLO), excessive heat (LHO and LLO), wildfires (LHO)
- LIGO Laboratory is committed to continued facilities maintenance and upgrades into the 2040s that will maintain its unique observatory infrastructure.
  - The 2024-28 LIGO Operations budgets includes significant funds to address ‘property lifecycle maintenance’ (ie carry out deferred and preventative maintenance). It is expected that these costs will grow as the facilities age in the 2030s and 2040s.
  - LIGO Laboratory remains deeply invested in community outreach in the regions where the two observatories are located in order ensure continued stable operations and relatively quiet seismic environments as communities continue to develop.
  - Land leases for LHO (from US DOE) and LLO (from LSU) extend through 2043 and 2044 respectively.

LIGO Operations in the CE Era

- As CE begins operations, the LIGO observatories may continue to play a valuable role as part of a hybrid 2G/3G international network.
  - In the early years of CE operation, while CE is working towards achieving design sensitivity, the wideband A$^\#$ configuration may provide the best high-frequency sensitivity for accessing compact binary post-merger signals.
  - The LIGO detectors can also provide coverage when the CE detectors have to be taken offline.
- The cost of LIGO operations in the CE era would depend on the scope.
  - LIGO Operations budget for 2024-2028 is $250M, supporting LHO and LLO detector operations, as well as EPO programs and Caltech and MIT campus-based detector R&D programs.
- A unified ‘GWLab’ management model, a future umbrella organization responsible for managing the US gravitational-wave observatory complex including the CE Project and the LIGO Laboratory (a la NRAO) could yield benefits
  - Providing a robust matrix management model will allow for optimal use of scientific and engineering staff in CE and LIGO and promote the effective exchange of experience and knowledge

Our Key Takeaways

- There are credible upgrade paths ($A^{\#}$) to achieve about a 2X improvement of the A+ detectors' sensitivities across the observing band.
- Beyond that, further improvement is *not likely* given the hard physical constraint imposed by 4 km arm lengths.
- With continued investment in and stewardship of their infrastructure, the LIGO Hanford and Livingston observatories can continue operations into the 2040s.
- In addition to carrying out a scientifically rich observing program, the LIGO detectors will serve as valuable technology development pathfinders for Cosmic Explorer.

We will submit a white paper to the ngGW MPSAC subcommittee that covers these topics in more detail.