Snowmass2021 - Letter of Interest

Cosmic Explorer: The Next-Generation U.S. Gravitational-Wave Detector

Topical Group(s):

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☑ (CF7) Cosmic Probes of Fundamental Physics
☑(AF6) Advanced Acc. Concepts
☑ (IF1) Quantum Sensors

Contact Information:
Name (Institution) [email]: Stefan Ballmer (Syracuse University) [sballmer@syr.edu]
Peter Fritschel (MIT) [pf@ligo.mit.edu]
Collaboration (optional): Cosmic Explorer and LIGO Laboratory

Authors: (Cosmic Explorer, LIGO Laboratory, OzGrav)
Dave Reitze, Albert Lazzarini, Joseph Giaime, Mike Landry, Peter Fritschel, Rainer Weiss, Matthew Evans, Stefan Ballmer, Geoffrey Lovelace, Yanbei Chen, B.S. Sathyaprakash, Jocelyn Read, Joshua Smith, Duncan Brown, Salvatore Vitale, Rana Adhikari, Bram Slagmolen

Abstract: Gravitational waves can probe a wide range of fundamental physics phenomena throughout the history of the universe. This includes access to the binary black hole population when the universe was still in its infancy, to the equation of state of matter at neutron star cores at supranuclear densities and quark deconfinement phase transitions in hot merger remnants, to the expansion history of the universe independent of the cosmic distance ladder and the ability to measure the properties of dark energy and dark matter, to stochastic gravitational-waves from early-universe phase transitions, and to the highly warped space-time in the strong-field and high-velocity limit of general relativity. A network of ground-based, third-generation, gravitational-wave detectors can achieve these scientific goals. The detector's sensitivity, roughly 10 times better than the planned LIGO A+ upgrade, requires significantly larger facilities and a number of technological upgrades. This LoI describes the most intriguing science targets for third-generation gravitational-wave detectors and the research needed to be able to build these observatories in the 2030s. The authors of this LoI represent the Cosmic Explorer collaboration and the LIGO Laboratory.

Third-generation gravitational-wave detectors will bring the discoveries we have made in the last 5 years into the mainstream of physics. The measurement of the gravitational waves from compact binary systems such as the coalescence of binary black holes and neutron stars have given us a benchmark for the detection sensitivity. The third-generation detectors are intended to probe the nuclear and gravitational physics from these systems, and are able to observe these mergers out to cosmological distances, accessing the remnants of the first stars in the universe.

The follow-up to the 2017 detection of the first binary neutron star coalescence elegantly demonstrated the importance of being able to couple gravitational-wave astronomy to electromagnetic and particle astronomy. To carry out this multi-messenger astronomy third-generation detectors will require a network of most likely 3 detectors well-distributed around the world. European groups are actively working on the design of a third-generation detector while Australian groups are beginning to study how they might contribute to a third-generation network.

The follow-up white paper will describe physics accessible and the research program needed to enable the design and construction of third-generation gravitational-wave detectors to carry out this scientific program. We expect to propose a specific third generation detector design in the mid 2020s based on the program we outline in this technical white paper.

We anticipate that the white paper will include the following items:

1) A description of the cosmological, dark matter, fundamental and nuclear physics accessible by future gravitational-wave detectors. This includes access to:

- primordial black holes throughout cosmic time and the fraction of dark matter that can be due to black holes,
- a stochastic background of gravitational waves from phase transitions in the early universe after inflation,
- Hubble constant and cosmic acceleration measurements on a wide range of redshifts and independent from existing cosmic distance ladders,
- the equation of state of nuclear matter at neutron star densities from tidal deformations,
- the equation of state of nuclear matter at post-merger densities and temperatures from remnant normal modes,
- precision measurements of gravitation at large curvatures and velocities close to the speed of light,
- possible deviation from general relativity in binary black hole dynamics.

2) The rationale driving the Cosmic Explorer detector concept, a 40km L-shaped gravitational-wave interferometer, to achieve the science described above.

3) A description of the program of laboratory research and prototyping to convert current detector components and designs to the longer arms, increase the capability to test larger, heavier main optics and suspension systems, and to develop the technology for the second phase of the 3rd generation which involves cryogenics, new materials for the main optics and different

wavelength lasers and optical components. The particular technologies that need to be developed include:

- Improved squeezed light and other quantum metrology techniques
- Large (hundreds of kg), low-loss fused silica optics for test masses
- Large (hundreds of kg) single crystal silicon as a test mass material
- Optical coatings for the larger test masses that have low optical loss and low thermal noise
- Cryogenics with low vibrational noise
- Improved active vibration isolation
- 2 um wavelength technology: high power, low noise lasers, and high quantum efficiency photodiodes
- Low cost UHV vacuum tubes, as the total construction cost of a 40km gravitational wave observatory is driven by the cost of the vacuum system.

4) A description of the engineering study required to design and construct a 40km arm length L-shaped interferometric gravitational-wave detector with a sensitivity improvement of close to a factor of 10 over the currently funded LIGO A+ Project. The study needs to identify construction sites, the most economical vacuum system to achieve the requirements for a 40km detector, and provide realistic cost estimates.

5) A program to forge an international collaboration for the construction and operation of a unified third generation network of gravitational-wave detectors.

We welcome contributions from researchers previously outside the field of gravitational-wave astronomy.

Related Letters of Interest on gravitational wave science topics, that we are aware of at this time:

A. Compact binaries as probes of dense matter and QCD phase transitions
B. Probing the expansion history of the Universe with Gravitational Waves
C. Search for gravitational waves from ultralight boson clouds around black holes
D. Search for gravitational waves from primordial black holes and dark matter
E. Probing Fundamental Physics using the Stochastic Gravitational Wave Background from the Early Universe
F. Correlating Stochastic Gravitational Wave Background with Electromagnetic Observations
G. Analytical waveform models for binary black holes
H. Gravitational Wave Propagation as a Probe of Fundamental Physics
I. Discovering axion/axion-like particles using gravitational-wave sources

Related Letters of Interest on gravitational wave instrumentation topics:

A. Ground-based gravitational-wave detectors as advanced quantum sensors

References:

GWIC 3G homepage:	https://gwic.ligo.org/3Gsubcomm/
Cosmic Explorer homepage:	https://cosmicexplorer.org/index.html
Einstein Telescope Letter of Interest:	http://www.et-gw.eu/index.php/letter-of-intent

Reitze, D., Adhikari, R., Ballmer, S., Barish, B., Barsotti, L., Billingsley, G., Brown, D., Chen, Y., Coyne, D., Eisenstein, R., Evans, M., Fritschel, P., Hall, E., Lazzarini, A., Lovelace, G., Read, J., Sathyaprakash, B., Shoemaker, D., Smith, J., Torrie, C., Vitale, S., Weiss, R., Wipf, C., & Zucker, M. (2019). **Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO**. In *Bulletin of the American Astronomical Society* (pp. 35).
https://ui.adsabs.harvard.edu/abs/2019BAAS...51g..35R

Srivastava, V., Ballmer, S., Brown, D., Afle, C., Burrows, A., Radice, D., & Vartanyan, D. (2019). **Detection prospects of core-collapse supernovae with supernova-optimized third-generation gravitational-wave detectors** *PhRvD, 100*(4), 043026.
https://ui.adsabs.harvard.edu/abs/2019PhRvD.100d3026S

Martynov, D., Miao, H., Yang, H., Vivanco, F., Thrane, E., Smith, R., Lasky, P., East, W., Adhikari, R., Bauswein, A., Brooks, A., Chen, Y., Corbitt, T., Freise, A., Grote, H., Levin, Y., Zhao, C., & Vecchio, A. (2019). **Exploring the sensitivity of gravitational wave detectors to neutron star physics** *PhRvD, 99*(10), 102004.
https://ui.adsabs.harvard.edu/abs/2019PhRvD..99j2004M

Reitze, D., LIGO Laboratory: California Institute of Technology, LIGO Laboratory: Massachusetts Institute of Technology, LIGO Hanford Observatory, & LIGO Livingston Observatory (2019). **The US Program in Ground-Based Gravitational Wave Science: Contribution from the LIGO Laboratory** *BAAS, 51*(3), 141.
https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.141R

Punturo, M., & Lück, H. (2019). Chapter: **Ideas for 2.5G and 3G interferometric detectors.** Book: *Advanced Interferometric Gravitational-Wave Detectors. Volume I: Essentials of Gravitational-Wave Detectors.* Edited by Reitze D et al. Published by World Scientific Publishing Co. Pte. Ltd
https://ui.adsabs.harvard.edu/abs/2019aigw.book..707P

Abbott, B., Abbott, R., Abbott, T., Abernathy, M., Ackley, K., Adams, C., Addesso, P., Adhikari, R., Adya, V., Affeldt, C., & et al. (2017). **Exploring the sensitivity of next generation gravitational wave detectors** *CQGra, 34*(4), 044001.
https://ui.adsabs.harvard.edu/abs/2017CQGra..34d4001A

Additional Authors:

None.

--