Science Letter for the Cosmic Explorer MPSAC white paper submission

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April 24 2024

Background

- As we have heard, NSF has created a blue ribbon panel to evaluate designs for next-generation gravitational-wave detectors
- The CE Project white paper was informed by the CE Consortium
  - Request for science letters (max 2 pages) to the Consortium on April 14 2023
  - 19 Letters received by the deadline of May 8 2023
  - White paper submitted on June 12 2023
- The charge was:
  "Each Science Letter should outline the capabilities and timelines needed for an XG network to address a specific science question. Science Letters are encouraged to suggest benchmarks that will ensure that the XG network is capable of the breakthrough science that they describe."

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Thanks to all who worked on these letters!

Science letter calls

- We organized several Zoom calls where the authors of the letters could describe them to the CE Consortium (Dec ‘23 to Feb ‘24)
- 5 calls, grouping the letter in (rough) macro-areas
  - Nuclear Physics
  - Fundamental Physics
  - Supernovae/Magnetars
  - Formation and evolution of compact binary coalescences
  - Multimessenger astrophysics
- Zoom recordings and all letters are available in the CE DCC!

Science letters

- In the next few slides I will give a broad overview of the topics that were covered
  - What exciting goals can be reached
  - What detector(s) are needed to make that happen *
- This is **not** an exhaustive list of what CE can do!
- Ben Owen will discuss some of the important science goals of CE that were **not** included in the Science Letters
- The ngGW report also identified relevant objectives (e.g. axion clouds)

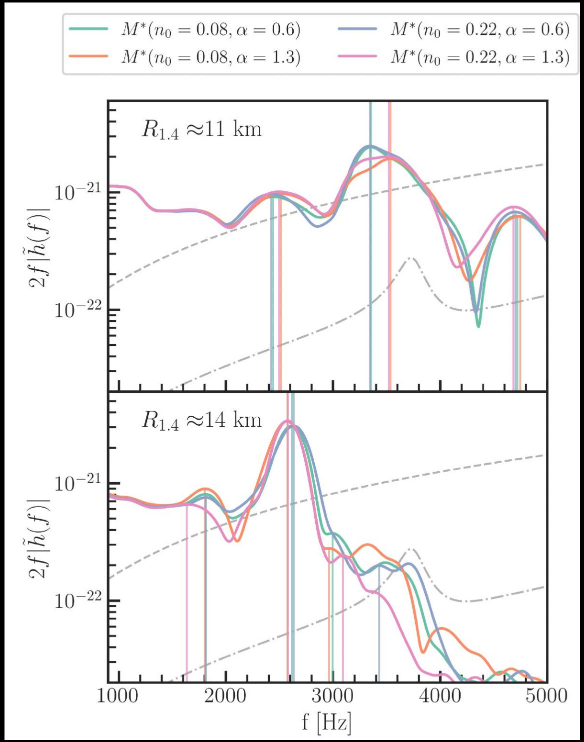
* A panel on Thu morning will discuss what is needed from other communities to maximize CE science

Nuclear Physics - what can be done?

- Precious information from the **inspiral** phase of compact binary coalescences
  - Information about the low-temperature/high-density QCD phase diagram - hard or impossible to probe with other means
- Phase transitions (e.g. to deconfined quarks) and how strongly coupled the system is, can be probed.
- These could live imprint in the mass spectrum of the BNS population
  - “Twin stars”
- Can investigate dopplegänger EOSs
  - Very similar inspiral signals but very different nuclear physics. CE can measure tides precisely enough to distinguish

Nuclear Physics - what can be done?

- Precious information from the **post-merger** phase of compact binary coalescences
- The peaks (in the frequency domain) of the post-merger signal is a rich source of nuclear physics information!
  - Exotic matter (quarks, hyperions) can shift the frequency of the main post-merger peak even when it leaves the inspiral signal unaffected
  - Enable probing **finite** temperature effects (as opposed to zero-temperature)



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Nuclear Physics - what is needed?

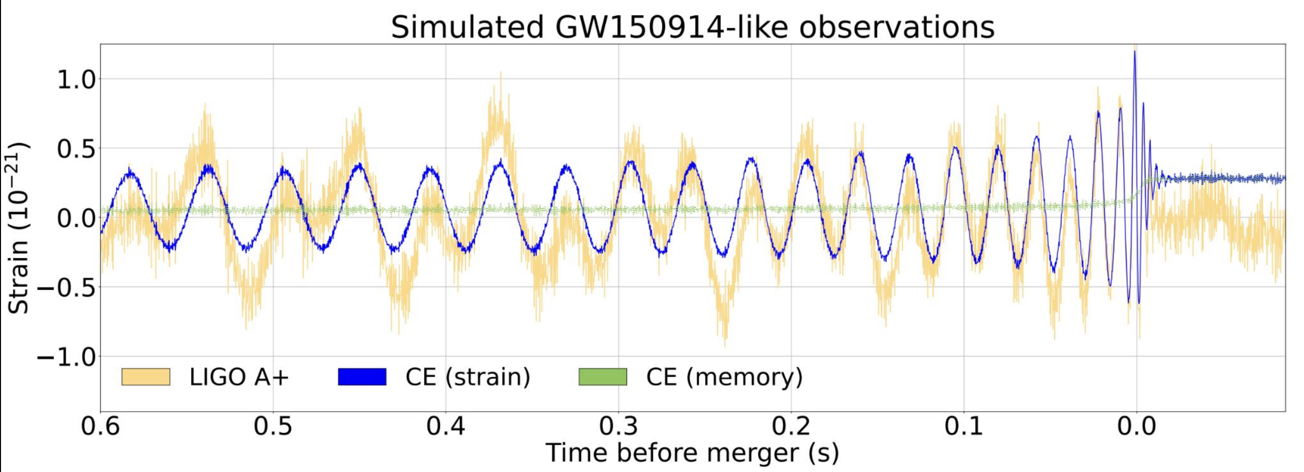
- High signal to noise ratio (SNR>100)
  - Gives precision on tidal deformability better than ~10
- A complete survey of binary neutron star mergers at redshifts past 0.2
  - Completeness ensures probing the whole NS mass range and hence mass-dependent effects
- High-frequency sensitivity (~1-3.5 kHz) to fully probe post-merger signals
  - CE tunability in the kHz region would be useful

Fundamental Physics - what can be done?

- Search for **all** six GW polarizations allowed in alternative metric theories of gravity
  - Breathing and longitudinal modes are not distinguishable with current facilities
- Precise measurement of the Hubble constant and dark energy EOS thanks to the large number of well-localized sources
- “Gravitational” phase transitions between neutron star with scalar hair and “usual” neutron stars

Fundamental Physics - what can be done?

- Memory effects (permanent displacement of space time)
  - Can verify GR prediction
  - Can be used to measure the rate of parabolic encounters (whose power is dominated by memory)



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Fundamental Physics - what is needed?

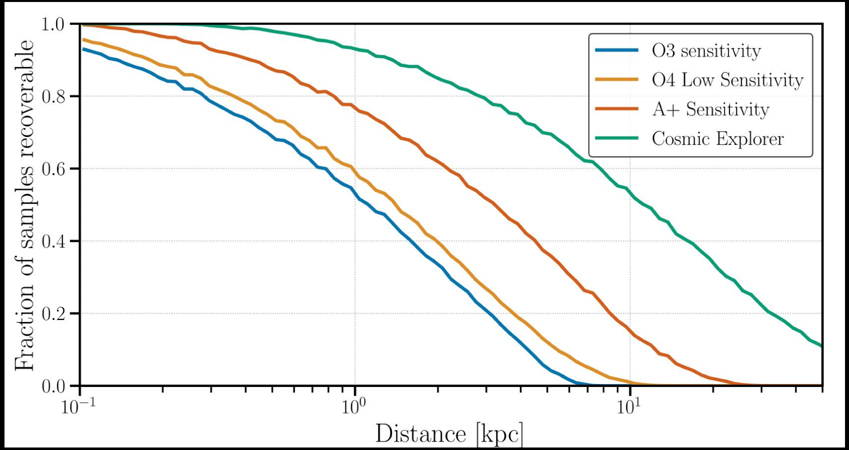
- ❖ All these measurements benefit from the high-SNRs guaranteed by CE
- ❖ Distinguishing all GW polarizations requires at least one 40 km CE
- ❖ Precision cosmology requires a network of XG to localize events (in sky and distance space)
- ❖ Accessing memory effects is easier with good sensitivity below 50Hz

Supernovae and Magnetars - what can be done?

- All of the GWs detected to date are from compact binaries, but there is a zoo of possible sources out there!
- The galactic center could be a promising source of GWs
  - Detectors close(r) to the equator would have a higher sensitivity to the Milky Way center
- The mass distribution of SNe remnants (NS and BH) can be used to study the SNe engine and its evolution with redshift

Supernovae and Magnetars - what can be done?

- Pulsars with extreme magnetic fields (magnetars) could emit GWs driven by internal oscillations
  - Searched but not found in LVK data
  - Contain information about NS EOS
  - CE could see them anywhere in the Milky Way



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Supernovae and Magnetars - what is needed?

- To detect GW from magnetars f-modes, one needs good sensitivity in the 1-3 kHz region
- A complete survey of binary neutron star mergers and precise measurement of their source frame masses and redshift is needed to probe SNe physics

Formation and evolution of CBC - what can be done?

- ❖ Due to its cosmological reach, CE will probe the formation channels of CBC and how they evolve with redshifts
- ❖ Enables star formation rate measurements far beyond the capacity of EM observations
- ❖ Characterize types and characteristics of mass transfer episodes in the lives of CBCs
- ❖ Increased probability of detecting non-circular binaries, i.e. eccentricity, an important tracer of the binary’s history.

Formation and evolution of CBC - what can be done?

- The low frequency (<20 Hz) sensitivity enables studying both sides of the upper mass gap
  - Pair instability supernova
  - Carbon-Oxygen nuclear reaction rate
- Intermediate-mass black holes may be lurking just above the upper mass gap!
  - Detection ⇏ characterization. Need a network!
- CE won't have a pronounced selection bias for higher masses (unlike current detectors)
  - Exquisite measurement of the mass function of light black holes and heavy neutron stars

Formation and evolution of CBC - what is needed?

- A network of detectors is necessary to measure the astrophysically relevant source-frame mass (we need to undo the redshift)
  - A letter mentions “(Sub-)percent measurements of the masses of a near-complete population of BHBHs out to redshift z ~ 2”
  - This requires resolving the GW polarizations!
  - If we end up with a single next-gen detector, we won’t be able to measure the source frame masses of objects at z>>0
- Low frequency (<20Hz) sensitivity is needed to reveal and measure eccentricity and to detect and characterize intermediate-mass black holes

Multimessenger astrophysics - what can be done?

- As we know, GWs can come with EM waves!
- New potential sources of detectable GW waves are being explored
  - Production from the cocoon and wobbling jets of collapsars
  - Could illuminate the physics of magnetic-drive stellar explosions
  - Active are or research, rates and reach to be fully determined
- Synergies with new VLA (2038) and other existing or planned facilities will enable extensive MMA study of all possible outcomes of BNS and NSBH mergers
  - EM emission
  - Fate of the merger product
  - Cosmology/Cosmography

Multimessenger astrophysics - what is needed?

- A network of next-gen detectors to precisely localize EM bright sources
  - The exact composition of the network affects the maximum distance at which good localization can still be achieved
- At least 2 next-gen detectors to localize BNS within 10 deg2 at z~1
  - Needed to have a large MMA sample
  - Bright siren cosmology and cosmography

More observational science at the Symposium

Later today:

1. Other science goals for CE
2. Nuclear physics
3. Dark energy, dark matter, early universe

Tomorrow 11AM ET (3PM UTC)

1. Panel discussion: What is needed from other communities?
2. Compact binaries
3. Continuous waves and CCSNe