



The 2022 Lectures in Physics

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ONASSIS EDUCATION



- LIGO has been very successful, but the next big step in gravitational-wave science will require new facilities
- Cosmic Explorer is a larger, and more technically advanced version of the current LIGO observatories

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EXPL

 Two observatories: one 40km (25 miles) and the other 20km on a side





Einstein Telescope (ET)

- Underground; in Eurome
- Six detectors arranged in a triangle
 - \Rightarrow sense both GW polarizations
 - \Rightarrow "null stream" for consistency checks
- Observe down to a few hertz using "xylophone" detectors approach
 - \Rightarrow low frequency: cryogenic silicon
 - \Rightarrow high frequency: high power, room temp
- ET Design Report published 2011, updated 2020
- In 2021, ET was included in the roadmap of the European Strategic Forum for Research Infrastructures (ESFRI).











A Horizon Study for

Cosmic Explorer

Science, Observatories, and Community

cosmicexplorer.org

















Precision tests will be enabled by black hole mergers like those seen now (~30 solar mass, at $z \sim 0.3$), which will have an SNR ~ 1000 in CE.





Total source-frame mass / M_{\odot}

10

LIGO A+ Cosmic Explorer Voyager Einstein Telescope

100

With thousands of BBH events per day, we will be able to cherry pick the most telling events (high spins, large kicks, edge-on, high ellipticity, etc.).





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Precision tests will be enabled by black hole mergers like those seen now (~30 solar mass, at $z \sim 0.3$), which will have an SNR ~ 1000 in CE.

LIGO A+ Cosmic Explorer

With thousands of BBH events per day, we will be able to cherry pick the most telling events (high spins, large kicks, edge-on, high ellipticity, etc.).



Extreme Gravity Fundamental Physics

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Cosmic Explorer Timeline



Development		Observatory Design & Site Preparation	Construction & Commissioning	Operations					
GW, Physics, Astronomy, & Local Community Engagement Ongoing Community Collaboration									
Initial Development	Horizon Study	Site Search & Sile Sel & Research	ected Construction	Community Facility Operation					
		Design Stage	Commis	sion Upgrade & Observation Commission	Observation				
		Construct Funded	ion Initial Fab. & Install	First Upgrade Fab. Lock & Install					
		Laboratory Resear & Prototyping	rch Up	Upgraded Design					
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10	20	25 3	55	40	45				
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EXPLOR									











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map from native-land.ca	native lands	Yoreme (May	o) Tobosos Alazapas	7	Mayaimi	
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Taino	Hauve-lanu.ca	Pericú				Taino



Coeur d'Alene)

ORER

native lands map from native-land.ca We live and work on the unceded ancestral lands of Indigenous peoples.

I, together with the Cosmic Explorer team, acknowledge these Indigenous communities and their stewardship of the land, past, present and future Payner Kikapo (Kickapo) Peria

The Cosmic Explorer team is committed to building long-lasting synergistic relationships with Indigenous communities in order to align our goals while building trust and mutual respect.

Tiwa Tribe Ndé Kónitsąąií Gokiyaa

leanth more about land acknowledgements at Matecumbe nativegov.org

Origin of CE in 2013

Long
 Uncomplicated
 Next-generation
 Gravitational-wave
 Observatory (LUNGO)

As a counterpoint to the complicated schemes being contemplated at the time



Gravitational Wave Strain



If you have masses that are free to move, you can (at least in principle) measure the spacetime distortion produced by the gravitational wave





Why 40km?

- Broadly speaking, the sensitivity of these instruments improves with length
- The bandwidth is, however, limited to roughly

$$\frac{c}{2L} = \frac{3 \times 10^5 \,\frac{km}{s}}{2 \times 40 \,km} \simeq 4 \,kHz$$

so making a detector longer than 40km would compromise its access to interesting astrophysics (i.e., post-merger signals and supernovae).



Bandwidth vs. Length

- Buonanno: $f_{merger} \sim 4.4 \text{ kHz} \left(\frac{M_{\odot}}{M}\right)$
 - lightest black hole binaries will merge below $\sim 2 \ \rm kHz$
- Binary Neutron Stars expected to produce post-merger signals around 2-3kHz
- Supernovae may produce significant signal amplitudes up to few kHz
- Detector response (Sutton: "antenna pattern") becomes complicated, and gets smaller, as $f \rightarrow \frac{c}{2L}$



Figure 6 A two-body system, m_1 and m_2 orbiting in the *xy*-plane around their C.O.M.



40km CE



July 2022

M. Evans

25



Shot Noise while maintaining bandwidth

Radiation Pressure Noise while maintaining bandwidth

Coating Thermal Noise constant loss angle...

Residual Gas Noise facility limit...









Shot Noise while maintaining bandwidth

Radiation Pressure Noise while maintaining bandwidth

Coating Thermal Noise constant loss angle...

Residual Gas Noise facility limit...



B P Abbott *et al* 2017 *CQG* **34** 044001

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\,\rm K}} \sqrt{\frac{\phi_{\rm eff}}{5 \times 10^{-5}}} \left(\frac{14\,\rm cm}{r_{\rm beam}}\right) \left(\frac{40\,\rm km}{L_{\rm arm}}\right)$$
$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4 \times 10^{-7}\,\rm Pa}} \sqrt{\frac{14\,\rm cm}{r_{\rm beam}}} \sqrt{\frac{40\,\rm km}{L_{\rm arm}}}$$



Shot Noise 40 km 2 MW $h_{\rm shot}$ while maintaining bandwidth 1.5 μm Parm $h_{0 \text{ shot}}$ -∕arm 3/2 320 kg **Radiation Pressure Noise** 1.5 μm $h_{\rm RPN}$ $P_{\rm arm}$ 40 km while maintaining bandwidth $h_{0\,\mathrm{RPN}}$ 2 MW *m*_{TM} B P Abbott et al 2017 CQG 34 44001 **Coating Thermal Noise** 14 cm $h_{\rm CTN}$ 40 km $\phi_{\rm eff}$ constant loss angle... 123 K V $h_{0\,\mathrm{CTN}}$ r_{beam} $h_{\rm gas}$ **Residual Gas Noise** $p_{\rm gas}$ 14 cm 40 km facility limit... $4 \times 10^{-7} \, \mathrm{Pa}$ $h_{0\,\mathrm{gas}}$ r_{beam} ⊿arm



Shot Noise while maintaining bandwidth

Radiation Pressure Noise while maintaining bandwidth

 $h_{\rm shot}$ 2 MW 40 km 1.5 µm Parm $h_{0 \text{ shot}}$ ⊿arm 1.5 μm 40 km $h_{\rm RPN}$ $P_{\rm arm}$ $h_{0\,\mathrm{RPN}}$ 2 MW B P Abbott et al 2017 CQG 34 044001 $h_{\rm CTN}$ 40 km $\phi_{\rm eff}(I)$ 123 K $h_{0 \text{CTN}}$

40 km

 $L_{\rm arm}^{3/2}$

 $p_{\rm gas}$

 4×10^{-7} Pa

Residual Gas Noise facility limit...

h_{gas}

 $h_{0\,\mathrm{gas}}$

Scaling Up... an example





Exploring the sensitivity of next generation gravitational wave etectors (2017) CQG 34, 044001





Technical Readiness of Cosmic Explorer

- Mostly "incremental" changes relative to LIGO
- The mirrors will be bigger, and the suspensions longer to help with low-frequency performance
- We expect somewhat better coatings for the mirrors (lower thermal noise, few or no point absorbers)
- While challenging, we are targeting a plausible improvement in quantum performance (10dB of squeezing)

EXPLORER





Newtonian Noise (local gravity)



Low frequencies are hard





Some Context...





The Next-Gen GW Network

Einstein Telescope (ET) is a similar project underway in Europe

- Planning to operate together
- On the European Strategy for Research Infrastructures (ESFRI) Roadmap
- Different design (underground triangle, 6 interferometers, 3 of them cryogenic)

Laser Interferometer Space Antenna (LISA)

- An ESA-led space observatory with a small NASA contribution
- Expected to be launched in 2034 and take data concurrently with CE and ET

Neutron-star Extreme Matter Observatory (NEMO)

- An Australian observatory but a smaller observatory focused on specific science
- Aspire to build a CE-like detector in the future































Localization and Early Warning





Borhanian and Sathyaprakash, in preparation



Conclusion

- Gravitational-wave science is still in its infancy
- We are at the dawn of a new age of exploration



- Cosmic Explorer is the US concept for a nextgeneration gravitational-wave detector
 - We are very excited about the future!



spares



LIGO Hanford Observatory H1 detector

the second se

LIGO Livingston Observatory L1 detector

12.00

M. Evans

Now approaching 100 events!



Now approaching 100 events!

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



COSMIC EXPLORER July 2022 Image: Eddie Anaya (Undergrad, Art, Cal State Fullerton)



COSMIC EXPLORER July 2022 Image: Eddie Anaya (Undergrad, Art, Cal State Fullerton)



Signal Frequency and Black Hole Mass

Estimate Period of Last Orbit

For 30 M $_{\odot}$, R_s ~ 90km take r₁ = r₂ = 2 R_s so that v = c / 2

 $T_{orb} = (4 \pi) 90 \text{ km / (c / 2)}$ ~ 7.5 ms $f_{orb} = 1 / T_{orb} \sim 125 \text{ Hz}$ $f_{GW} = 2 f_{orb} \sim 250 \text{ Hz}$

(actual value for GW150914 was ~200 Hz)



"The basic physics of the binary black hole merger GW150914" (arXiv:1608.01940)



M. Evans



Signal Amplitude and Distance

Estimate Distance to Source

For 30 M $_{\odot}$, R_s ~ 90km take GW strain at the source h = $\frac{1}{4}$ (since v / c = $\frac{1}{2}$)

 $d_L \sim R_s / (4 h_{obs}) \sim 2.5 G light-years$

(actual value for GW150914 was 1.3 Gly)



Figure 6 A two-body system, m_1 and m_2 orbiting in the *xy*-plane around their C.O.M.

"The basic physics of the binary black hole merger GW150914" (arXiv:1608.01940)