Realizing Cosmic Explorer 2 with Evolved LIGO A+ or Voyager Technology

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for the
Cosmic Explorer Project

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Cosmic Explorer

![Graph showing strain noise vs frequency for Cosmic Explorer facilities CE1 and CE2. The graph compares the performance of the two facilities with different arm lengths.]
Cosmic Explorer

40 km L-shaped surface facility

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**Strain noise / Hz**

<table>
<thead>
<tr>
<th>Frequency / Hz</th>
<th>CE1</th>
<th>CE2 (2 μm)</th>
<th>CE2 (1 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*arXiv:2012.03608*
Cosmic Explorer

- 40 km L-shaped surface facility
- Immediate sensitivity improvement “just” by increasing the arm length

![Graph showing strain noise over frequency](https://via.placeholder.com/150)

arXiv:2012.03608
Cosmic Explorer

- 40 km L-shaped surface facility
- Immediate sensitivity improvement "just" by increasing the arm length
- Additional 20 km detector for post-merger physics

![Graph showing strain noise vs frequency for Cosmic Explorer phases CE1 and CE2]
Cosmic Explorer

- 40 km L-shaped surface facility
- Immediate sensitivity improvement “just” by increasing the arm length
- Additional 20 km detector for post-merger physics
- Realized in two stages with two technology options for the second stage

arXiv:2012.03608
Cosmic Explorer

- 40 km L-shaped surface facility
- Immediate sensitivity improvement “just” by increasing the arm length
- Additional 20 km detector for post-merger physics
- Realized in two stages with two technology options for the second stage
- CE1: built in the 2030’s using LIGO A+ technology

**Graph:**
- Strain noise / Hz
- Frequency / Hz

**Legend:**
- CE1
- CE2 (2 μm)
- CE2 (1 μm)
40 km L-shaped surface facility

Immediate sensitivity improvement “just” by increasing the arm length

Additional 20 km detector for post-merger physics

Realized in two stages with two technology options for the second stage

CE1: built in the 2030’s using LIGO A+ technology

CE2: built in the 2040’s using either evolved A+ or Voyager technology
Cosmic Explorer

- 40 km L-shaped surface facility
- Immediate sensitivity improvement “just” by increasing the arm length
- Additional 20 km detector for post-merger physics
- Realized in two stages with two technology options for the second stage
- CE1: built in the 2030’s using LIGO A+ technology
- CE2: built in the 2040’s using either evolved A+ or Voyager technology
- Facility can support future detectors

\[
\begin{align*}
\text{Strain noise} &\quad \text{Hz} \\
1 &\quad 2
\end{align*}
\]

CE1
CE2 (2 \(\mu\)m)
CE2 (1 \(\mu\)m)

\[
\begin{align*}
\text{Frequency} &\quad \text{Hz} \\
10^2 &\quad 10^3
\end{align*}
\]

arXiv:2012.03608
Cosmic Explorer 2

LIGO A+ Technology

1 μm laser
Room-temperature fused-silica optics

Voyager Technology

2 μm laser
Cryogenic silicon optics

Facility upgrades result in similar sensitivities for both designs.
Newtonian noise

- Suppression techniques are facility upgrades common to both technologies resulting in the same Newtonian noise for both.
- Seismometer array subtraction
- Excavation underneath test masses
- Berms, trenches, and seismic metamaterials
Test mass thermal noise

- Cosmic Explorer 1
- Cosmic Explorer 2 (1 μm)
- Total TM Thermal
- Substrate Brownian
- Substrate Thermo-Elastic
- Coating Brownian
- Coating Thermo-Optic

Cosmic Explorer 2 (2 μm)
- Total TM Thermal
- ITM Thermo-Refractive
- Substrate Brownian
- Substrate Thermo-Elastic
- Coating Brownian
- Coating Thermo-Optic

Frequency / Hz

Strain noise / Hz$^{-1/2}$
Both detector technologies have similar seismic noise.

Both technologies use suspensions with final stage blade springs to reduce vertical resonances: Sebastien’s talk.

CE2 target requires $100\times$ improvement over aLIGO inertial isolation performance at 1 Hz.

Several novel isolator ideas: Mow-Lowry & Martynov, van Heijningen, ...
Suspension thermal noise

- Cosmic Explorer 1
- Cosmic Explorer 2 (1 μm)
- Total Suspension Thermal
- Horiz. Top
- Horiz. APM
- Horiz. PUM
- Horiz. Test mass
- Vert. Top
- Vert. APM
- Vert. PUM

Strain noise / Hz

Frequency / Hz

10^1 10^2

Strain noise / Hz^{1/2}

10^{-26} 10^{-21}

10^{-25} 10^{-24}

10^{-23}

10^{-22}

10^{-21}
Quantum noise

- Same quantum noise for both technologies
- Shot noise $\propto \sqrt{\lambda/P_{\text{arm}}}$
  - $P_{\text{arm}} = 1.5 \text{ MW for } \lambda = 1 \mu\text{m}$
  - $P_{\text{arm}} = 3 \text{ MW for } \lambda = 2 \mu\text{m}$
- 10 dB frequency dependent squeezing for both technologies
- 500 ppm SEC loss limits HF sensitivity
Noise scalings with arm length: a 20 km CE2

Fixed bandwidth $T_{\text{sem}} \propto 1/L$

Spotsize $w \propto \sqrt{L}$ for constant cavity geometry
Noise scalings with arm length: a 20 km CE2

CTN $\propto 1/Lw$

ITM TR $\propto 1/\sqrt{F L w^2}$

Fixed bandwidth $T_{\text{sem}} \propto 1/L$

Spotsize $w \propto \sqrt{L}$ for constant cavity geometry
Noise scalings with arm length: a 20 km CE2

<table>
<thead>
<tr>
<th>Strain noise (Hz)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE2 (1 μm) Total</td>
<td>10^{-26}</td>
<td>10^{-25}</td>
<td>10^{-24}</td>
</tr>
<tr>
<td>CE2 (2 μm) Total</td>
<td>10^{-23}</td>
<td>10^{-22}</td>
<td>10^{-21}</td>
</tr>
<tr>
<td>Quantum Vacuum</td>
<td>10^{-21}</td>
<td>10^{-20}</td>
<td>10^{-19}</td>
</tr>
<tr>
<td>Seismic</td>
<td>10^{-14}</td>
<td>10^{-13}</td>
<td>10^{-12}</td>
</tr>
<tr>
<td>Newtonian</td>
<td>10^{-12}</td>
<td>10^{-11}</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>Suspension Thermal</td>
<td>10^{-9}</td>
<td>10^{-8}</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>Coating Thermal</td>
<td>10^{-7}</td>
<td>10^{-6}</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>Substrate Thermal</td>
<td>10^{-5}</td>
<td>10^{-4}</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>Residual Gas</td>
<td>10^{-3}</td>
<td>10^{-2}</td>
<td>10^{-1}</td>
</tr>
</tbody>
</table>

\[
\text{CTN} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{ITMTR} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{shot noise} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{QRPN} \propto L^{-3/2}
\]

\[
\text{other loss} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{gas scat.} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{gas damp.} \propto \frac{1}{\sqrt{\text{L}}}
\]

\[
\text{Fixed bandwidth } T_{\text{sem}} \propto \frac{1}{L}
\]

\[
\text{Spotsize } w \propto \sqrt{L} \text{ for constant cavity geometry}
\]
Noise scalings with arm length: a 20 km CE2

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<td>$10^3$</td>
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</tr>
</tbody>
</table>

- **CTN**: $\propto \frac{1}{L_w}$
- **SEC loss**: $\propto \sqrt{F L^0}$
- **ITMTR**: $\propto \frac{1}{\sqrt{F L_w^2}}$
- **QRPN**: $\propto L^{-3/2}$
- **Shot noise**: $\propto \frac{1}{\sqrt{L}}$
- **Other loss**: $\propto \frac{1}{\sqrt{L}}$

Fixed bandwidth $T_{sem} \propto \frac{1}{L}$

Spots size $w \propto \sqrt{L}$ for constant cavity geometry
Noise scalings with arm length: a 20 km CE2

Fixed bandwidth $T_{sem} \propto 1/L$

Spotsize $w \propto \sqrt{L}$ for constant cavity geometry
Noise scalings with arm length: a 20 km CE2

Fixed bandwidth $T_{\text{sem}} \propto 1/L$
Spotsize $w \propto \sqrt{L}$ for constant cavity geometry
Noise scalings with arm length: a 20 km CE2

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Frequency / Hz</th>
<th>Strain noise / Hz</th>
<th>Other Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Vacuum</td>
<td></td>
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</tr>
<tr>
<td>Seismic</td>
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<td>Suspension Thermal</td>
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</table>

\[ \text{CTN} \propto \frac{1}{L} \]
\[ \text{SEC loss} \propto \sqrt{F L^0} \]
\[ \text{horiz. susp.} \propto \frac{1}{L} \]
\[ \text{vert. susp.} \propto \frac{1}{L} \]
\[ \text{Newtonian} \propto \frac{1}{L} \]
\[ \text{ITM TR} \propto \frac{1}{\sqrt{F L w^2}} \]
\[ \text{shot noise} \propto \frac{1}{\sqrt{L}} \]
\[ \text{QRPN} \propto \frac{L^{-3/2}}{} \]
\[ \text{gas scat.} \propto \frac{\sqrt{w}}{L} \]
\[ \text{gas damp.} \propto \frac{1}{L} \]

Fixed bandwidth: \( T_{\text{sem}} \propto \frac{1}{L} \)

Spot size: \( w \propto \sqrt{L} \) for constant cavity geometry

8 / 10
High power cryogenic silicon CE2

<table>
<thead>
<tr>
<th>Total CE2</th>
<th>$P_{\text{arm}} = 10$ MW, $F = 1500$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CE2</td>
<td>$P_{\text{arm}} = 3$ MW, $F = 450$</td>
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</tbody>
</table>

Quantum Vacuum
Seismic
Newtonian
Suspension Thermal
Coating Thermal
Substrate Thermal
Residual Gas

Strain noise $\text{Hz} = 2$

Total CE2
$P_{\text{arm}} = 10$ MW, $F = 1500$
Total CE2
$P_{\text{arm}} = 3$ MW, $F = 450$

AS Port Vacuum (10 dB Sqz)
Arm Loss
SEC Loss
Filter Cavity Loss
Injection Loss
Readout Loss
Quadrature Phase

Absorbed power in ITM's can't exceed radiative cooling power

$P_{\text{abs}} = \pi\alpha_{\text{sub}} h_{\text{TM}} P_{\text{arm}} F$

SEC loss at HF $\propto \sqrt{F P_{\text{arm}}}$
SEC loss at LF $\propto \sqrt{F P_{\text{arm}}}$

Large beams: intensity $\sim 2 \times$ less than Voyager for $P_{\text{arm}} = 10$ MW

Thermallensing, coating absorption, angularinstabilities, PI's, …?
High power cryogenic silicon CE2

Absorbed power in ITM’s can’t exceed radiative cooling power

\[ P_{abs} = \pi \alpha_{sub} h_{TM} \frac{P_{arm}}{\mathcal{F}} + \alpha_{coat} P_{arm} \]
High power cryogenic silicon CE2

Absorbed power in ITM’s can’t exceed radiative cooling power

\[ P_{\text{abs}} = \pi \alpha_{\text{sub}} h_{\text{TM}} \frac{P_{\text{arm}}}{F} + \alpha_{\text{coat}} P_{\text{arm}} \]

SEC loss

at HF \( \propto \sqrt{\frac{F}{P_{\text{arm}}}} \), at LF \( \propto \sqrt{FP_{\text{arm}}} \)
High power cryogenic silicon CE2

- Absorbed power in ITM’s can’t exceed radiative cooling power

\[ P_{abs} = \pi \alpha_{sub} h_h \frac{P_{arm}}{f} + \alpha_{coat} P_{arm} \]

- SEC loss

\[ \text{at HF } \propto \sqrt{\frac{f}{P_{arm}}} \quad \text{at LF } \propto \sqrt{f \frac{P_{arm}}}{P_{arm}} \]

- Large beams: intensity \( \sim 2 \times \) less than Voyager for \( P_{arm} = 10 \text{ MW} \)
High power cryogenic silicon CE2

- Absorbed power in ITM’s can’t exceed radiative cooling power
  \[ P_{abs} = \pi \alpha_{sub} h_{TM} \frac{P_{arm}}{F} + \alpha_{coat} P_{arm} \]

- SEC loss
  \[ \text{at HF } \propto \sqrt{\frac{F}{P_{arm}}} \quad \text{at LF } \propto \sqrt{FP_{arm}} \]

- Large beams: intensity ~ 2× less than Voyager for \( P_{arm} = 10 \text{ MW} \)

- Thermal lensing, coating absorption, angular instabilities, PI’s, ...?
Summary

- CE2 can reach similar strain sensitivities using either evolved LIGO A+ or Voyager technology.
- Risk mitigation in the event that significant challenges are discovered in one of the technologies.
- However, many required R&D activities (Newtonian noise suppression, inertial isolation, ...) are common to both realizations of CE2.
- Many generations of detector technologies are expected to be used in the CE observatories.
- Voyager technology has greater potential for increased arm powers in the future.