km-scale Space Gravitational Wave Detector

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Science-Driven Approach
C-DECIGO
(10 kg, 10 km Fabry-Perot)
Motivations

- Demonstration of multiband gravitational wave detection
  - Detect BBHs and BNSs a few days before the merger
- IMBH search with unprecedented sensitivity

- km-scale space mission
- Demonstration of interferometry and formation flight for B-DECIGO and DECIGO

## Existing Space GW Projects

<table>
<thead>
<tr>
<th></th>
<th>LISA</th>
<th>TianQin</th>
<th>B-DECIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm length</td>
<td>2.5e6 km</td>
<td>1.7e5 km</td>
<td>100 km</td>
</tr>
<tr>
<td>Interferometry</td>
<td>Optical transponder</td>
<td>Optical transponder</td>
<td>Fabry-Pérot cavity</td>
</tr>
<tr>
<td>Laser frequency stabilization</td>
<td>Reference cavity, 1064 nm</td>
<td>Reference cavity, 1064 nm</td>
<td>Iodine, 515 nm</td>
</tr>
<tr>
<td>Orbit</td>
<td>Heliocentric</td>
<td>Geocentric, facing J0806.3+1527</td>
<td>Geocentric (TBD)</td>
</tr>
<tr>
<td>Flight configuration</td>
<td>Constellation flight</td>
<td>Constellation flight</td>
<td>Formation flight</td>
</tr>
<tr>
<td>Test mass</td>
<td>1.96 kg</td>
<td>2.45 kg</td>
<td>30 kg</td>
</tr>
<tr>
<td>Force noise req.</td>
<td>8e-15 N/rtHz Achieved</td>
<td>7e-15 N/rtHz</td>
<td>1e-16 N/rtHz</td>
</tr>
</tbody>
</table>
Sensitivity Comparison

aLIGO: [LIGO-T1800044](https://www.ligo.org/)
CE: [CQG 34, 044001 (2017)](https://iopscience.iop.org/article/10.1088/1361-6382/aa5f0c)
Horizon Distance

- B-DECIGO
- LISA
- CE
- ET
- aLIGO
- KAGRA
- TianQin
- B-DECIGO x 30

Optimal direction and polarization
SNR threshold 8

Horizon Distance [Gpc]

Chirp Mass [Msun]

GW150914
GW170817

z=10
z=1
We can barely detect O1/O2 binaries with B-DECIGO x 30 sensitivity. We can also search for $O(10^3)$ Msun IMBH upto $z=10$. Optimal direction and polarization, SNR threshold 8.
C-DECIGO

- Target sensitivity
  \[ \text{C-DECIGO} = \text{B-DECIGO} \times 30 \]
  \[ = \text{DECIGO} \times 300 \]

- For GW150914 and GW170817 like binaries, C-DECIGO can measure coalescence time to \(< \sim 150 \text{ sec} \) a few days before the merger

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Multiband gravitational-wave astronomy: Observing binary inspirals with a decihertz detector, B-DECIGO

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An evolving Japanese gravitational-wave (GW) mission in the decihertz band, B-DECIGO (DEciHerz laser Interferometer Gravitational wave Observatory), will enable us to detect GW150914-like binary black holes, GW170817-like binary neutron stars, and intermediate-mass binary black holes out to cosmological distances. The B-DECIGO band slots in between the aLIGO–Virgo–KAGRA–IndIGO (hectohertz) and LISA (millihertz) bands for broader bandwidth; the sources described emit GWs for weeks to years across the multiple bands to accumulate high signal-to-noise ratios. This suggests the possibility that joint detection would greatly improve the parameter estimation of the binaries. We examine B-DECIGO’s ability to measure binary parameters and assess to what extent multiband analysis could improve such measurement. Using non-precessing post-Newtonian waveforms with the Fisher matrix approach, we find for systems like GW150914 and GW170817 that B-DECIGO can measure the mass ratio to within \(< 0.1\%\), the individual black-hole spins to within \(< 10\%\), and the coalescence time to within \(< 5 \text{ s} \) about a week before alerting aLIGO and electromagnetic facilities. Prior information from B-DECIGO for aLIGO can further reduce the uncertainty in the measurement of, e.g., certain neutron star tidally induced deformations by a factor of \(\sim 6\), and potentially determine the spin-induced neutron star quadrupole moment. Joint LISA and B-DECIGO measurement will also be able to recover the masses and spins of intermediate-mass binary black holes at percent-level precision. However, there will be a large systematic bias in these results due to post-Newtonian approximation of exact GW signals.

Sensitivity Target

- Requires $\sqrt{mL} > 3\sqrt{30} \sqrt{\text{kg} \cdot \text{km}}$ detector from SQL
• Requires $1e^{-16} \text{N/rtHz}$ for $mL = 90 \text{ kg} \cdot \text{km}$

Force noise cannot be worse if you want to do multiband GW astronomy. There’s no other choice!
Quantum Noise and Topology

- Optical transponder (LISA/TianQin-style)
  Cannot dig the bucket unless you increase the size of the test mass

- Michelson interferometer
  - arm length: 30 km
  - mirror mass: 3 kg (diffraction loss is small enough)
  - input power: 3 W (arm should be long to reduce power)
  gives you C-DECIGO target

- Fabry-Perot interferometer (DECIGO-style)
  - arm length: 3 km
  - mirror mass: 30 kg
  - finesse: 300
  - input power: 0.01 W
  gives you C-DECIGO target (one example)
# Michelson or Fabry-Perot

- Fabry-Perot seems reasonable choice

<table>
<thead>
<tr>
<th></th>
<th>Michelson</th>
<th>Fabry-Perot</th>
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<tbody>
<tr>
<td>Initial alignment</td>
<td>Same accuracy required</td>
<td></td>
</tr>
<tr>
<td>Difficulties</td>
<td>Recombination</td>
<td>Cavity</td>
</tr>
<tr>
<td>3 satellites</td>
<td>BS have to be in free fall</td>
<td>BS can be fixed</td>
</tr>
<tr>
<td>Arm length change</td>
<td>Possible (if mode mismatch is accepted)</td>
<td>Possible (if mode mismatch is accepted)</td>
</tr>
</tbody>
</table>

- Can also measure absolute length
Mirror Mass and Arm Length

- Force noise requirement
  \[ h_f = \frac{f}{m\omega^2 L} = \frac{1 \times 10^{-16}}{90 \text{ kg} \cdot \text{km} \omega^2} \]

- Radiation pressure noise
  \[ h_{rp} = \frac{4 F}{m\omega^2 L \pi} \sqrt{\frac{16\pi h P}{c\lambda}} = k_{\text{safe}} h_f \]

- If you fix requirement for \( f \), requirement for \( mL \) is set
- If you fix \( P \), finesse \( F \) is set
- Assuming g-factor g=0.3 and \( L \), beam size is calculated
- This gives you the minimum mirror mass from diffraction loss (assume fused silica, aspect ratio t/d = 1)
- Also, if you fix initial alignment accuracy, minimum mirror diameter \( d \) is determined from \( d/L \)

Say, this is 3

There's no point in reducing the finesse and input power if force noise is larger, in terms of sensitivity.
Mirror Mass and Arm Length

- 10 km, 10 kg seems better than 3 km, 30 kg:
  - From force noise
  - Not allowed from initial alignment
  - Not allowed from diffraction loss (depends much on aspect ratio)
  - cf. GRACE-FO launched May 2018 does 220 km FF
  - More sensitive
  - B-DECIGO
  - 10 kg, 10 km
  - cf. star tracker can do better than 1 arcsec (~5 urad)

- 30 kg, 3 km

- 0.01 W, finesse 402
- 0.1 W, finesse 127
- 1 W, finesse 40.2

From SQL:

- $1 \times 10^{-15}$ N/rtHz
- $8 \times 10^{-15}$ N/rtHz
C-DECIGO Design

Optimal direction and polarization
SNR threshold 8
C-DECIGO Summary

• Multiband gravitational wave astronomy
  - Measure coalescence time of O1/O2 binaries within a few minutes, a few days before the merger

• IMBH search
  - $O(10^3)$ Msun IMBH within the whole universe
  - Better than ET/CE and LISA

• C-DECIGO design parameters
  - Arm length: 10 km
    (Does this reduce the cost? Or increase the feasibility?)
  - Mirror mass: 10 kg
  - Force noise: $<1e^{-16}$ N/rtHz (same as B-DECIGO)
  - finesse: 400
  - input power: 0.01 W (no high power amp necessary?)

• Better to do B-DECIGO if the cost is similar
Findings

- To do original science in 3G-LISA era,
  - Force noise < ~1e-16 N/rtHz
  - \( mL > 90 \text{ kg} \cdot \text{km} \)
  - \( \sqrt{mL} > 3\sqrt{30} \sqrt{\text{kg} \cdot \text{km}} \)
  are required

- Fabry-Perot seems more feasible

- Although beam size will be smaller for shorter arm length, it requires heavier mass to keep force noise requirement the same (~ a few kg is the minimum for the test mass)

- Longer arm length is better due to SQL but
  - initial alignment accuracy will be tougher
  - higher power laser will be necessary due to lower finesse (diffraction loss)
Engineering-Driven Approach
F-DECIGO
(2 kg, 10 km Fabry-Perot)
Motivations

• Demonstration of formation flight
• Demonstration of laser interferometry between satellites

• Full success: technology demonstration (primary target)
• Extra success: IMBH search with unprecedented sensitivity
  - to realize this, we have to launch before LISA and TianQin (before ~2034)

• Launch within ~5-10 years
• Based on proven technologies
  - 2 kg mass (same mass with LISA/TianQin)
  - 8e-15 N/rtHz force noise (LISA-level)
Larger force noise requires larger $P$ and $\mathcal{F}$ to reach SQL. For example, for $8 \times 10^{-15} \text{ N/rtHz}$, $P=0.01 \text{ W}$ and $F=3 \times 10^4$ are required and this finesse is not feasible with small test mass.

We should forget about reaching SQL.

2 kg test mass, 10 km arm, Finesse 100 seems reasonable.
• Force noise limited sensitivity (could be used to evaluate force noise)
Optimal direction and polarization
SNR threshold 8
F-DECIGO Summary

• **Demonstration** of key technologies for DECIGO
  - formation flight
  - Fabry-Perot cavity between satellites
  - measure force noise in orbit

• **IMBH search**
  - $O(10^3) \text{Msun}$ IMBH to $\sim 3 \text{ Gpc}$ (*event rate to be calculated*)
  - Should launch before LISA/TianQin and ET/CE (before $\sim 2034$)

• **F-DECIGO design parameters**
  - Arm length: 10 km
    (Does this reduce the cost? Or increase the feasibility?)
  - Mirror mass: 2 kg (same mass as LISA)
    Fused silica, 10cm dia. 10cm thick
  - Force noise: $<8e-15 \text{ N/rtHz}$ (same as LISA)
  - finesse: 100
  - input power: 0.01 W (no high power amp necessary?)
Questions

• Mirror density?
  - smaller the better to make the mirror large considering diffraction loss
    (SQL and force noise do not depend on the density)
  - so far fused silica (2.2e3 kg/m³) is assumed

• Michelson?
  - alignment requirement is almost the same with FP
    (depends on FP cavity geometry, but independent on finesse)
  - FP alignment will be tougher if finesse is very high
    (input test mass transmission will be smaller)