

A Differentiable Interferometer Simulator for the Computational Design of Gravitational Wave Detectors

Jonathan Klimesch, Yehonathan Drori, Rana X. Adhikari, Mario Krenn

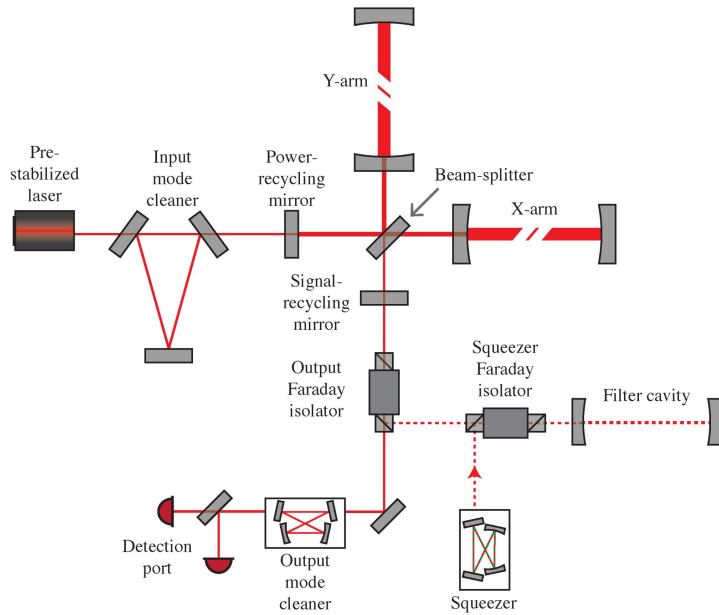
Second EuCAIFCon on June 17, 2025



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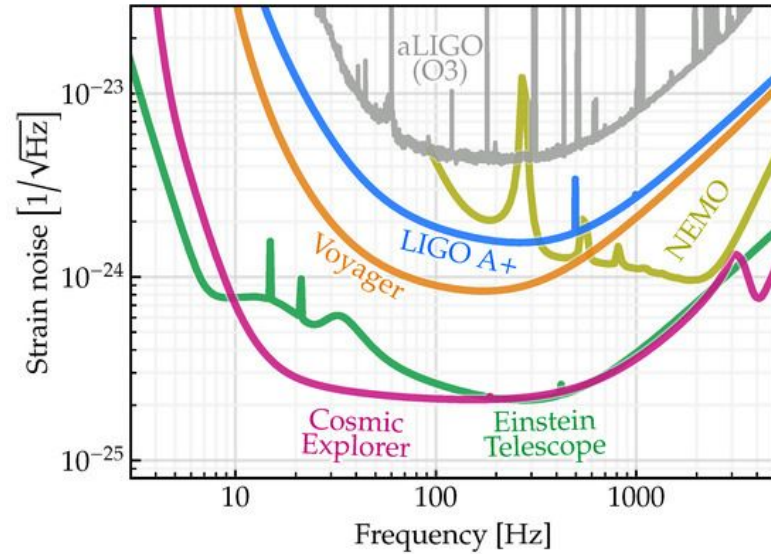
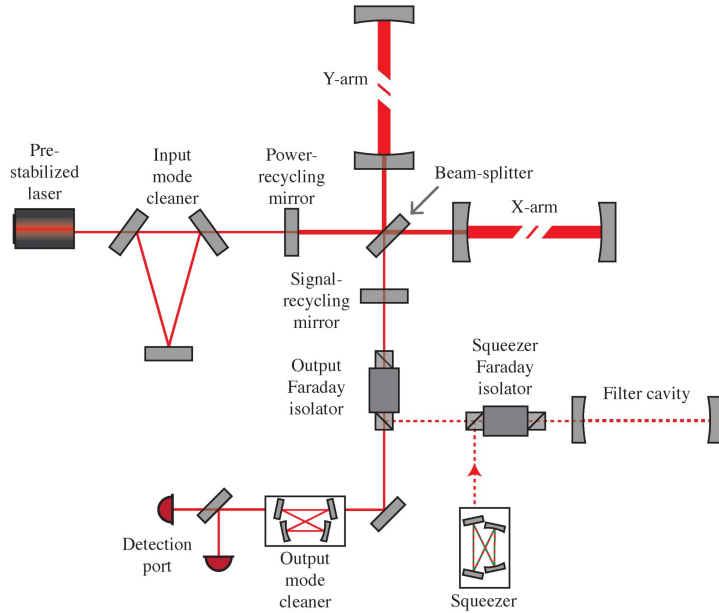


Simplified LIGO Detector



[Cahillane C, Mansell G. Review of the advanced LIGO gravitational wave observatories leading to observing run four. Galaxies. 2022 Feb 15;10\(1\):36.](#)

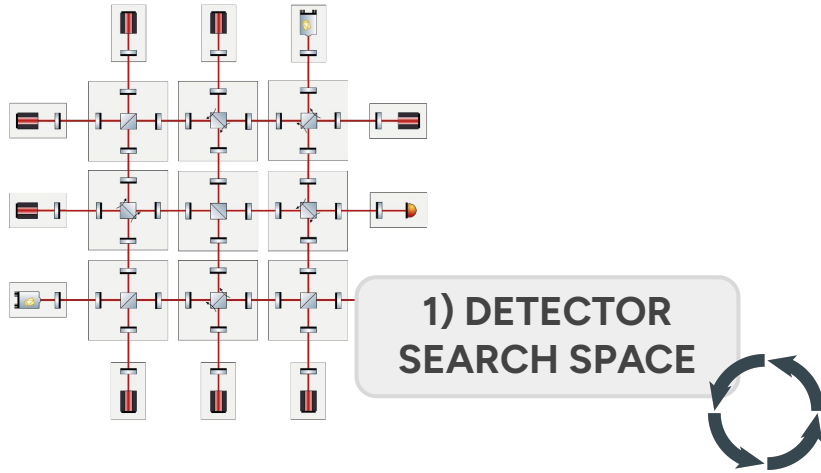
Strain Sensitivity Measures Detector Quality



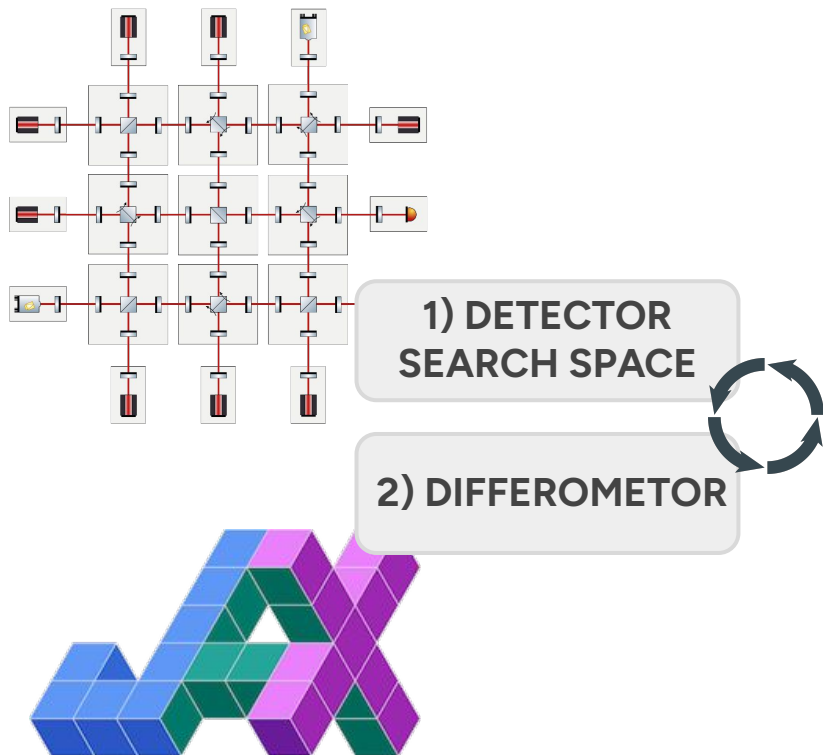
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**Can we use algorithms to find
unorthodox, but useful layouts?**

We Let Algorithms Design Superior Detector Layouts ...

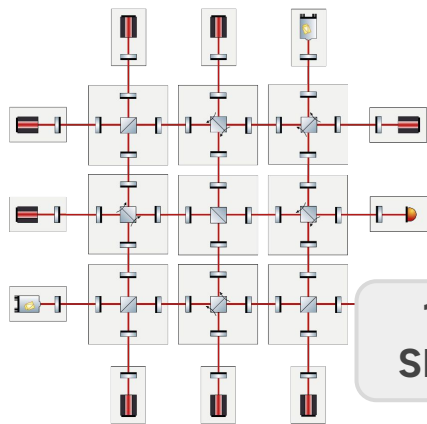


... Using Differentiable Programming



Differentiable Interferometer Simulator

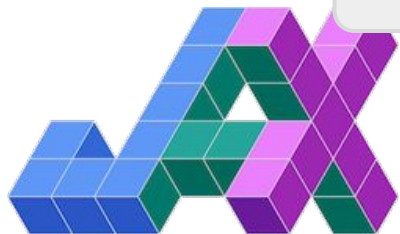
... Using Differentiable Programming



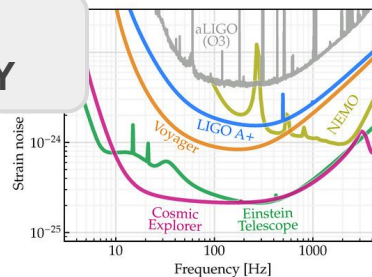
1) DETECTOR
SEARCH SPACE

2) DIFFEROMETER

3) STRAIN
SENSITIVITY

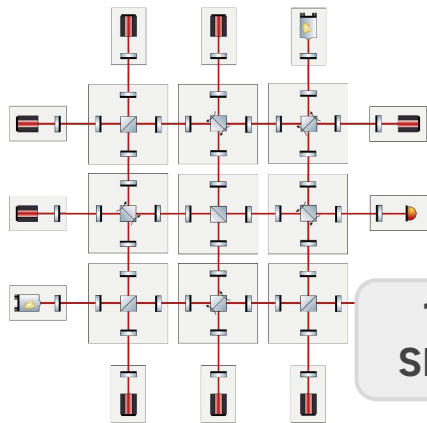


Differentiable Interferometer Simulator



$$\mathcal{L}_{\text{Strain}} = \int_{f_0}^{f_1} \log(S(f)) df$$

... Using Differentiable Programming

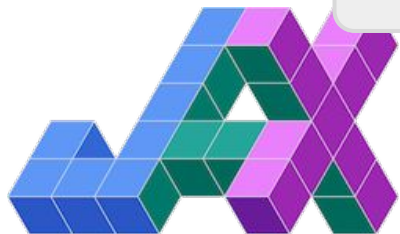


1) DETECTOR
SEARCH SPACE

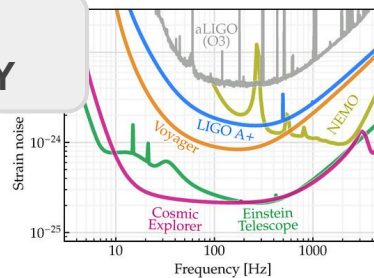
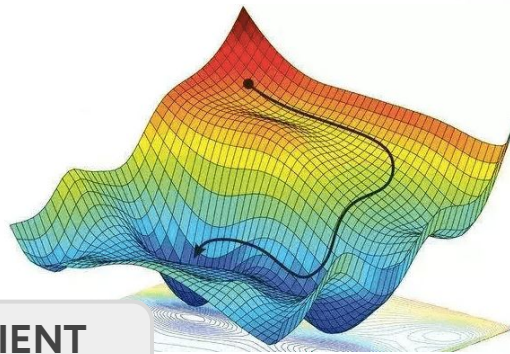
2) DIFFEROMETER

4) GRADIENT
DESCENT

3) STRAIN
SENSITIVITY



Differentiable Interferometer Simulator



$$\mathcal{L}_{\text{Strain}} = \int_{f_0}^{f_1} \log(S(f)) df$$

See you in Thursday's Poster Session!

A Differentiable Interferometer Simulator for the Computational Design of Gravitational Wave Detectors

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Differometer is a new **differentiable frequency domain interferometer simulator** implemented in Python using the JAX framework. Its automatic differentiation enables **gradient-based optimizations of interferometer layouts** that are up to **160 times faster** than optimizations with numerical differentiation and existing simulators.

Detector Search Space

UIFO layout

aLIGO layout in UIFO

We optimize quasi-universal interferometers (UIFOs), highly expressive, parametrized layouts that can hold impactful detector designs beyond human intuition.

Example: $f(x, y, z) = x + xy + z^2y$

Numerical Differentiation

$$\frac{\partial f}{\partial x} = \frac{f(x+h, y, z) - f(x, y, z)}{h}$$

$$\frac{\partial f}{\partial y} = \frac{f(x, y+h, z) - f(x, y, z)}{h}$$

$$\frac{\partial f}{\partial z} = \frac{f(x, y, z+h) - f(x, y, z)}{h}$$

$$\nabla f \approx \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right)$$

Instead of evaluating the simulator multiple times for each parameter gradient, **Differometer calculates all gradients in one simulation run**, enabling large-scale discovery optimizations that can yield superior detector designs.

AI-Based Exploration

Automatic Differentiation

Only one sweep required

Differometer

GitHub:

We evaluate the detector search space with our new differentiable interferometer simulator.

Cavity simulation

Import differometer as diff module: `from diff import diff`

3. `def setup():`
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`205. add_mirror("M202", x=1, y=0, z=51, phi=0)`
`206. add_mirror("M203", x=0, y=1, z=51, phi=0)`
`207. add_mirror("M204", x=1, y=1, z=51, phi=0)`
`208. add_mirror("M205", x=0, y=0, z=52, phi=0)`
`209. add_mirror("M206", x=1, y=0, z=52, phi=0)`
`210. add_mirror("M207", x=0, y=1, z=52, phi=0)`
`211. add_mirror("M208", x=1, y=1, z=52, phi=0)`
`212. add_mirror("M209", x=0, y=0, z=53, phi=0)`
`213. add_mirror("M210", x=1, y=0, z=53, phi=0)`
`214. add_mirror("M211", x=0, y=1, z=53, phi=0)`
`215. add_mirror("M212", x=1, y=1, z=53, phi=0)`
`216. add_mirror("M213", x=0, y=0, z=54, phi=0)`
`217. add_mirror("M214", x=1, y=0, z=54, phi=0)`
`218. add_mirror("M215", x=0, y=1, z=54, phi=0)`
`219. add_mirror("M216", x=1, y=1, z=54, phi=0)`
`220. add_mirror("M217", x=0, y=0, z=55, phi=0)`
`221. add_mirror("M218", x=1, y=0, z=55, phi=0)`
`222. add_mirror("M219", x=0, y=1, z=55, phi=0)`
`223. add_mirror("M220", x=1, y=1, z=55, phi=0)`
`224. add_mirror("M221", x=0, y=0, z=56, phi=0)`
`225. add_mirror("M222", x=1, y=0, z=56, phi=0)`
`226. add_mirror("M223", x=0, y=1, z=56, phi=0)`
`227. add_mirror("M224", x=1, y=1, z=56, phi=0)`
`228. add_mirror("M225", x=0, y=0, z=57, phi=0)`
`229. add_mirror("M226", x=1, y=0, z=57, phi=0)`
`230. add_mirror("M227", x=0, y=1, z=57, phi=0)`
`231. add_mirror("M228", x=1, y=1, z=57, phi=0)`
`232. add_mirror("M229", x=0, y=0, z=58, phi=0)`
`233. add_mirror("M230", x=1, y=0, z=58, phi=0)`
`234. add_mirror("M231", x=0, y=1, z=58, phi=0)`
`235. add_mirror("M232", x=1, y=1, z=58, phi=0)`
`236. add_mirror("M233", x=0, y=0, z=59, phi=0)`
`237. add_mirror("M234", x=1, y=0, z=59, phi=0)`
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`239. add_mirror("M236", x=1, y=1, z=59, phi=0)`
`240. add_mirror("M237", x=0, y=0, z=60, phi=0)`
`241. add_mirror("M238", x=1, y=0, z=60, phi=0)`
`242. add_mirror("M239", x=0, y=1, z=60, phi=0)`
`243. add_mirror("M240", x=1, y=1, z=60, phi=0)`
`244. add_mirror("M241", x=0, y=0, z=61, phi=0)`
`245. add_mirror("M242", x=1, y=0, z=61, phi=0)`
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`248. add_mirror("M245", x=0, y=0, z=62, phi=0)`
`249. add_mirror("M246", x=1, y=0, z=62, phi=0)`
`250. add_mirror("M247", x=0, y=1, z=62, phi=0)`
`251. add_mirror("M248", x=1, y=1, z=62, phi=0)`
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`256. add_mirror("M253", x=0, y=0, z=64, phi=0)`
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`258. add_mirror("M255", x=0, y=1, z=64, phi=0)`
`259. add_mirror("M256", x=1, y=1, z=64, phi=0)`
`260. add_mirror("M257", x=0, y=0, z=65, phi=0)`
`261. add_mirror("M258", x=1, y=0, z=65, phi=0)`
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`266. add_mirror("M263", x=0, y=1, z=66, phi=0)`
`267. add_mirror("M264", x=1, y=1, z=66, phi=0)`
`268. add_mirror("M265", x=0, y=0, z=67, phi=0)`
`269. add_mirror("M266", x=1, y=0, z=67, phi=0)`
`270. add_mirror("M267", x=0, y=1, z=67, phi=0)`
`271. add_mirror("M268", x=1, y=1, z=67, phi=0)`
`272. add_mirror("M269", x=0, y=0, z=68, phi=0)`
`273. add_mirror("M270", x=1, y=0, z=68, phi=0)`
`274. add_mirror("M271", x=0, y=1, z=68, phi=0)`
`275. add_mirror("M272", x=1, y=1, z=68, phi=0)`
`276. add_mirror("M273", x=0, y=0, z=69, phi=0)`
`277. add_mirror("M274", x=1, y=0, z=69, phi=0)`
`278. add_mirror("M275", x=0, y=1, z=69, phi=0)`
`279. add_mirror("M276", x=1, y=1, z=69, phi=0)`
`280. add_mirror("M277", x=0, y=0, z=70, phi=0)`
`281. add_mirror("M278", x=1, y=0, z=70, phi=0)`
`282. add_mirror("M279", x=0, y=1, z=70, phi=0)`
`283. add_mirror("M280", x=1, y=1, z=70, phi=0)`
`284. add_mirror("M281", x=0, y=0, z=71, phi=0)`
`285. add_mirror("M282", x=1, y=0, z=71, phi=0)`
`286. add_mirror("M283", x=0, y=1, z=71, phi=0)`
`287. add_mirror("M284", x=1, y=1, z=71, phi=0)`
`288. add_mirror("M285", x=0, y=0, z=72, phi=0)`
`289. add_mirror("M286", x=1, y=0, z=72, phi=0)`
`290. add_mirror("M287", x=0, y=1, z=72, phi=0)`
`291. add_mirror("M288", x=1, y=1, z=72, phi=0)`
`292. add_mirror("M289", x=0, y=0, z=73, phi=0)`
`293. add_mirror("M290", x=1, y=0, z=73, phi=0)`
`294. add_mirror("M291", x=0, y=1, z=73, phi=0)`
`295. add_mirror("M292", x=1, y=1, z=73, phi=0)`
`296. add_mirror("M293", x=0, y=0, z=74, phi=0)`
`297. add_mirror("M294", x=1, y=0, z=74, phi=0)`
`298. add_mirror("M295", x=0, y=1, z=74, phi=0)`
`299. add_mirror("M296", x=1, y=1, z=74, phi=0)`
`300. add_mirror("M297", x=0, y=0, z=75, phi=0)`
`301. add_mirror("M298", x=1, y=0, z=75, phi=0)`
`302. add_mirror("M299", x=0, y=1, z=75, phi=0)`
`303. add_mirror("M300", x=1, y=1, z=75, phi=0)`
`304. add_mirror("M301", x=0, y=0, z=76, phi=0)`
`305. add_mirror("M302", x=1, y=0, z=76, phi=0)`
`306. add_mirror("M303", x=0, y=1, z=76, phi=0)`
`307. add_mirror("M304", x=1, y=1, z=76, phi=0)`
`308. add_mirror("M305", x=0, y=0, z=77, phi=0)`
`309. add_mirror("M306", x=1, y=0, z=77, phi=0)`
`310. add_mirror("M307", x=0, y=1, z=77, phi=0)`
`311. add_mirror("M308", x=1, y=1, z=77, phi=0)`
`312. add_mirror("M309", x=0, y=0, z=78, phi=0)`
`313. add_mirror("M310", x=1, y=0, z=78, phi=0)`
`314. add_mirror("M311", x=0, y=1, z=78, phi=0)`
`315. add_mirror("M312", x=1, y=1, z=78, phi=0)`
`316. add_mirror("M313", x=0, y=0, z=79, phi=0)`
`317. add_mirror("M314", x=1, y=0, z=79, phi=0)`
`318. add_mirror("M315", x=0, y=1, z=79, phi=0)`
`319. add_mirror("M316", x=1, y=1, z=79, phi=0)`
`320. add_mirror("M317", x=0, y=0, z=80, phi=0)`
`321. add_mirror("M318", x=1, y=0, z=80, phi=0)`
`322. add_mirror`