Prompt your Experiment – The Artificial Scientist

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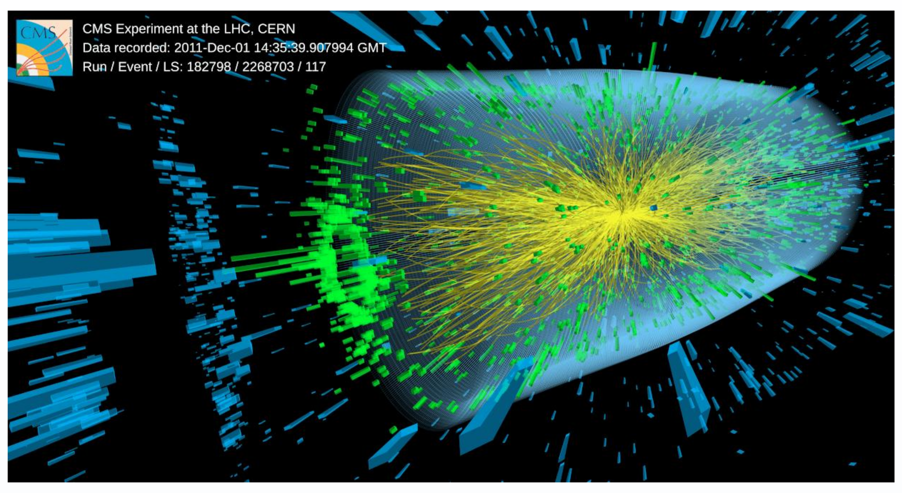
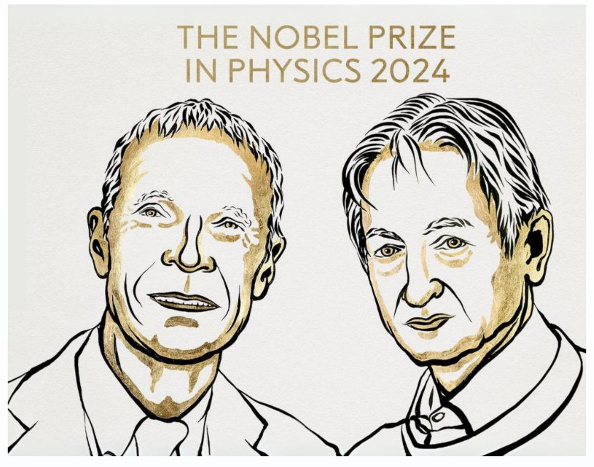
AI IN PHYSICS

Artificial Neural Networks (ANN) have long been a **key tool** among all domains of physics: whether multi-body systems in condensed matter physics or pattern recognition for huge amounts of data in particle physics. The building blocks of Artificial Intelligence (AI) often provide the **best methods to tackle these problems**.

This is why the **origin and study of AI** is closely connected to physical research. Also expressed by the Nobel Prize in physics 2024.



The Large Hadron Collider produces around 15 PB raw data per year after preselection.



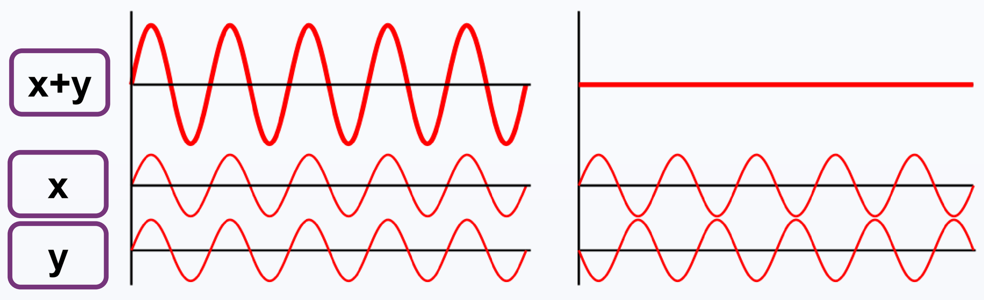
John J. Hopfield and Geoffrey Hinton, building AI since the 80ies

Besides modeling real-world-physics or helping as a tool in the data processing pipeline, the emergence of large language models (LLMs) now allows to **tailor AI-capabilities more precisely to numerous other tasks in experimental research**.

This poster presents the application of AI for the task of designing a Gravitational Wave Detector (GWD) almost autonomously [1].

GRAVITATIONAL WAVE DETECTORS

Gravitational Wave Detectors (GWD) are effectively one **huge interferometer**: light beams are split onto two arms (x and y) at a beam-splitter (BS). The two propagating electromagnetic waves in both arms experience **different optical paths**, are reflected back at mirrors onto the BS and recombined for detection.

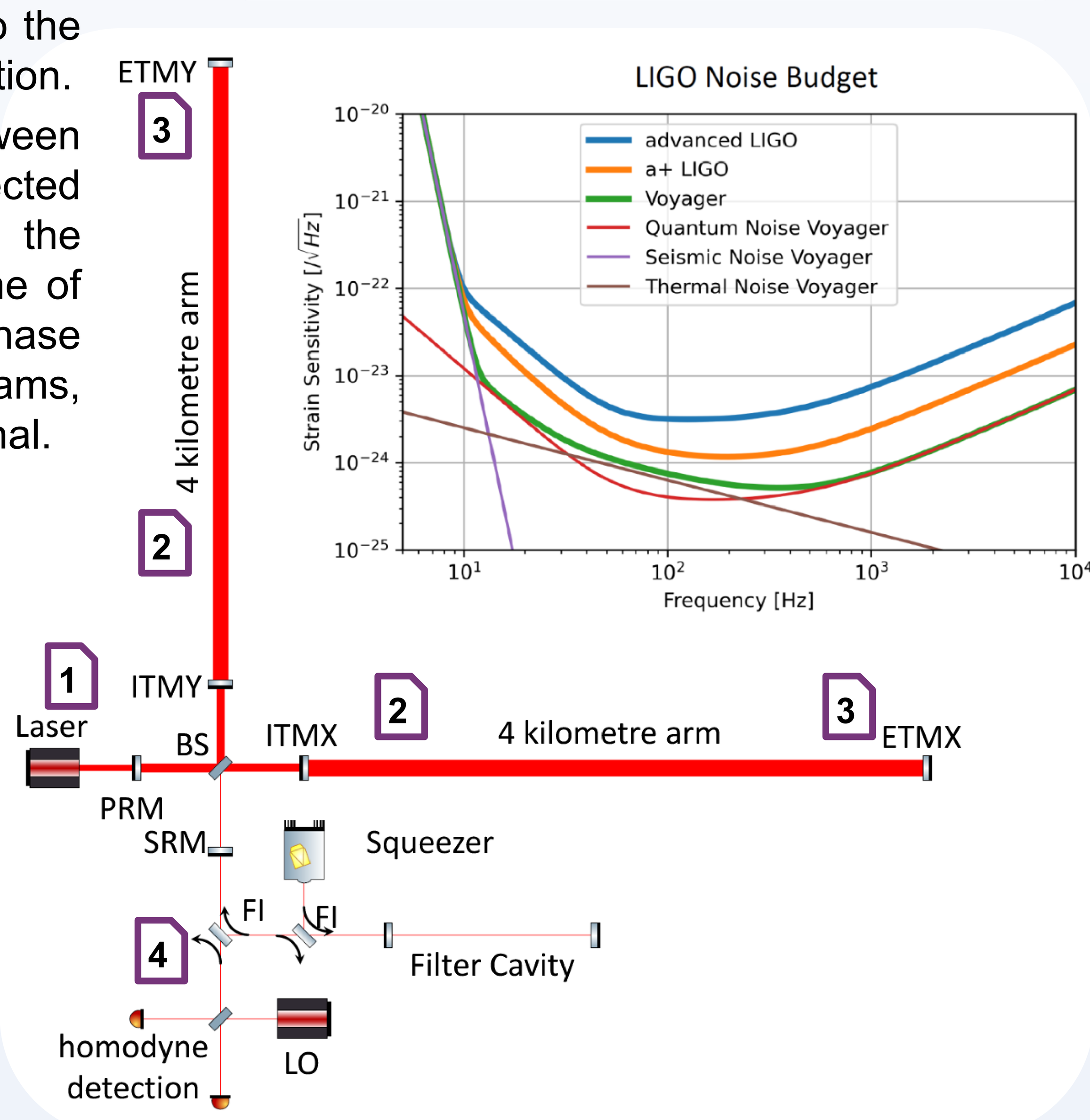


Constructive and deconstructive interference

The **phase relation** between them determines the detected signal. Changes on the nanometer scale in either one of the arms, change the phase relation between the beams, resulting in a measurable signal.

Gravitational waves were **predicted by Einsteins theory of general relativity** and could be experimentally proven for the first time in 2017. They literally **bend spacetime** and thereby change the length of the arms, generating a signal. This signal is characteristic for the underlying event, like black hole mergers or possibly supernovae.

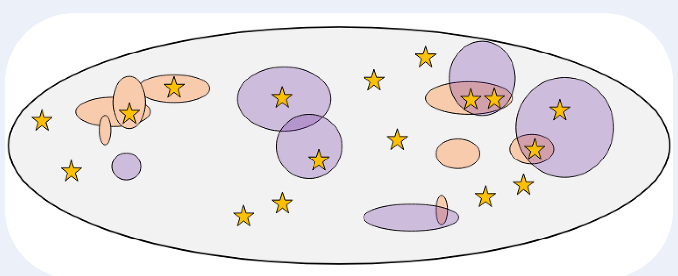
This allows for a fully **new way of observing the universe**, making it a valuable tool for astronomy.



Schematic of a GWD and detection sensitivity of different designs. Sensitivity is ultimately limited by seismic activity of the earth and quantum noise of light waves.

FINDING THE NEEDLE(S) IN THE HAYSTACK

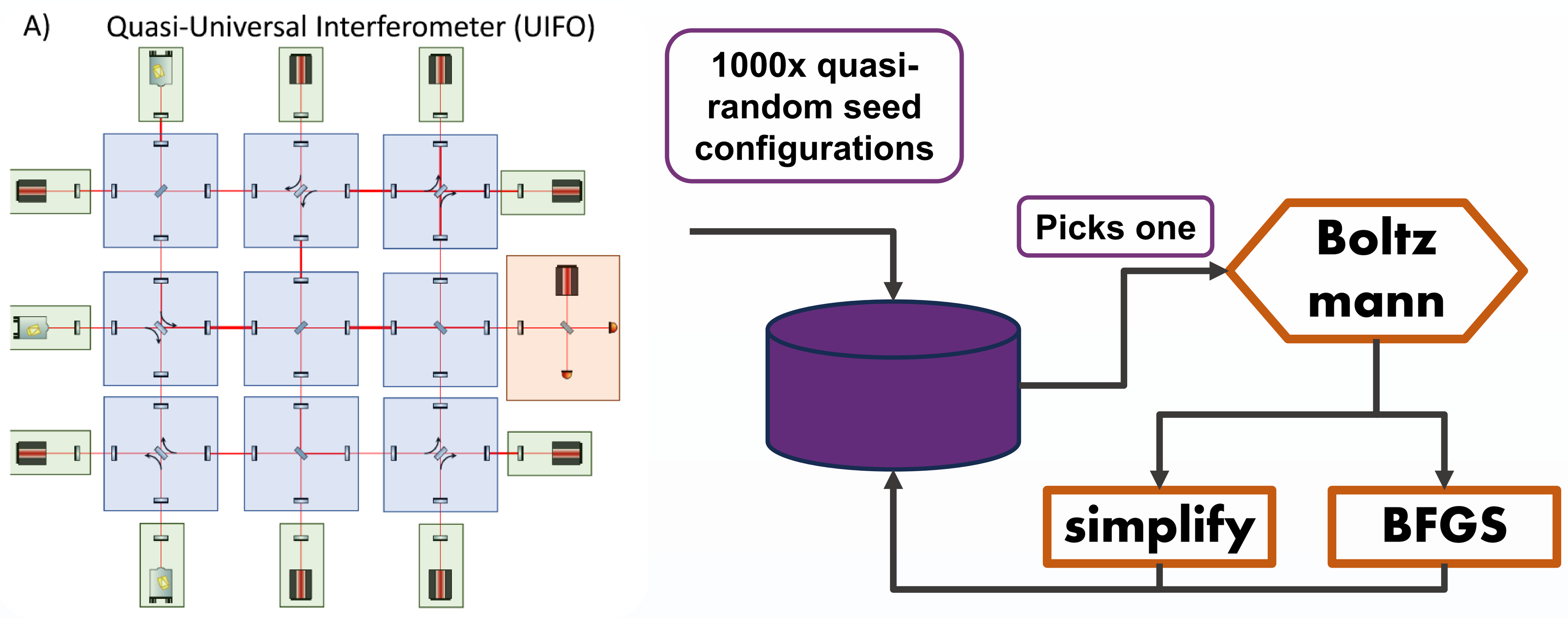
Building GWDs is highly complex. With growing numbers of components, the **search space of possible designs is huge** and a massive combinatorial problem in the first place. This is before considering the continuous parameter space of each optical component like reflectivity, laser powers etc. that must be optimized for each configuration individually. Human designers can only explore a tiny part of this huge design space and therefor rely on computers for such tasks ever since [1,2].



Abstract illustration of the search space of all possible GWD design configurations. The authors claim AI-assisted search ◯ allows to discover new useful designs⭐, hidden for human-led design◯

BUILDING URANIA

To leverage the **universal function approximation** of ANN the problem is firstly reframed into a **continuous optimization problem**. This is done by creating a quasi-universal interferometer(UIFO), capable of representing the entire search space.



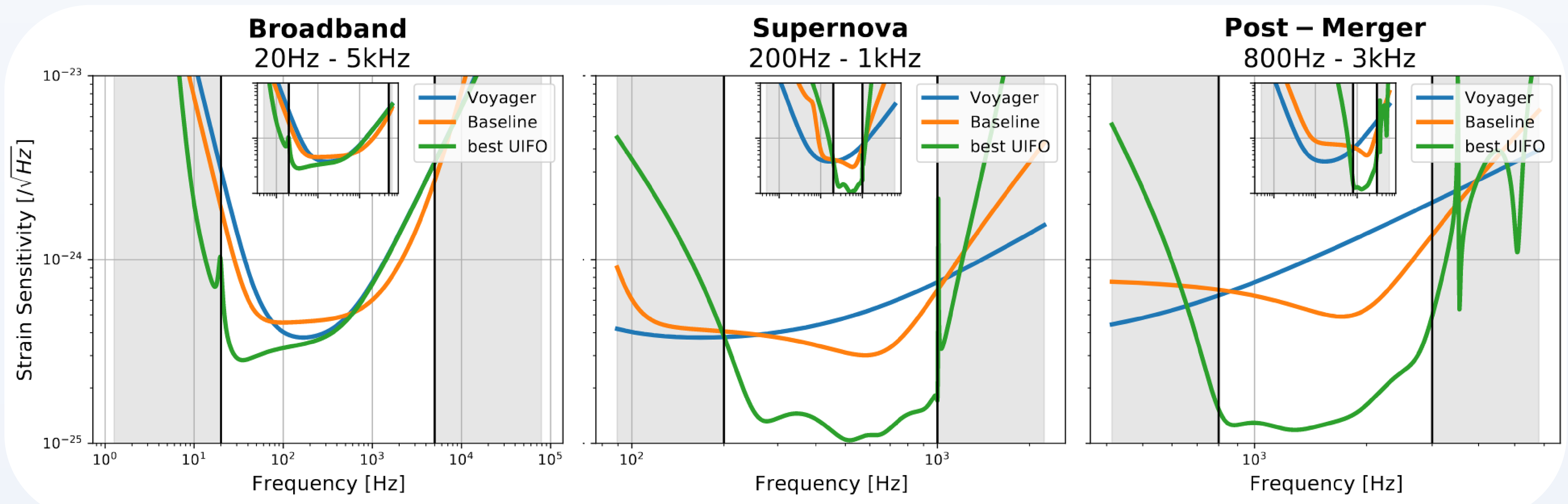
Flowchart of Urania optimizer. The algorithm optimizes both globally and locally, aiming for best trade-off between computing time and exploration of the search space.

Different detection frequency bands are defined as **optimization targets**. They correspond to different cosmical events of interest and allow to explore specialized setups.

The **seeding pool** is a mix of entirely random and known working UIFO configurations. A physics informed module called PyKat calculates the **strain sensitivity** for every setup, which is the crucial parameter to optimize. To prevent overcomplicated setups, that may score well on strain sensitivity but will become **unfeasible in the real world**, a **complexity score** is introduced. These two are the main components of the loss function.

The **Urania algorithm**, developed to find new designs, starts by picking one setup from the pool, based on a **Boltzmann** distribution that favors higher probability of simplification and optimization. The chosen setup is either simplified, by removing parts not substantially influencing sensitivity and added as new setup to the pool. Or the design parameters are optimized using an adapted **Broyden–Fletcher–Goldfarb–Shanno** (BFGS) algorithm until convergence. The optimized setup then replaces its predecessor in the search pool and Urania starts again. These processes running in parallel enable a **hybrid global and local optimization**.

After running through **1.5 million CPU hours**, the pool contained 50 setups showing better strain sensitivity in their respective target band than the latest planned GWD design Voyager. The 50 designs show similarities to known designs but also inherit **'unconventional' features**, hinting towards new design paradigms in the future.



Detection sensitivity of different AI designs (green) among different bands. The solutions show significant improvement compared to existing designs (blue, orange).

CONCLUSION

The paper shows a **substantially enhanced computer-assisted optimization** of complex experimental setups. Despite not fulfilling on a single prompt to ideal setup benchmark this application proves to be a helpful agent, capable of **inspiring new ideas** and massively expanding the accessible search space.

The findings are **applicable to many other quantum optical experiments** and one step towards an autonomous artificial scientist.

REFERENCES

[1] M. Krenn, Y. Drori, and R. X. Adhikari, "Digital Discovery of interferometric Gravitational Wave Detectors," *Phys. Rev. X*, vol. 15, no. 2, Apr. 2025

[2] M. Krenn, M. Erhard, and A. Zeilinger, "Computer-inspired quantum experiments," *Nature Reviews Physics*, vol. 2, no. 11, pp. 649–661, 2020.

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