EuCAIFCon, Cagliari, Italy, 19.06.2025

Towards an Artificial Muse for new Ideas in Physics

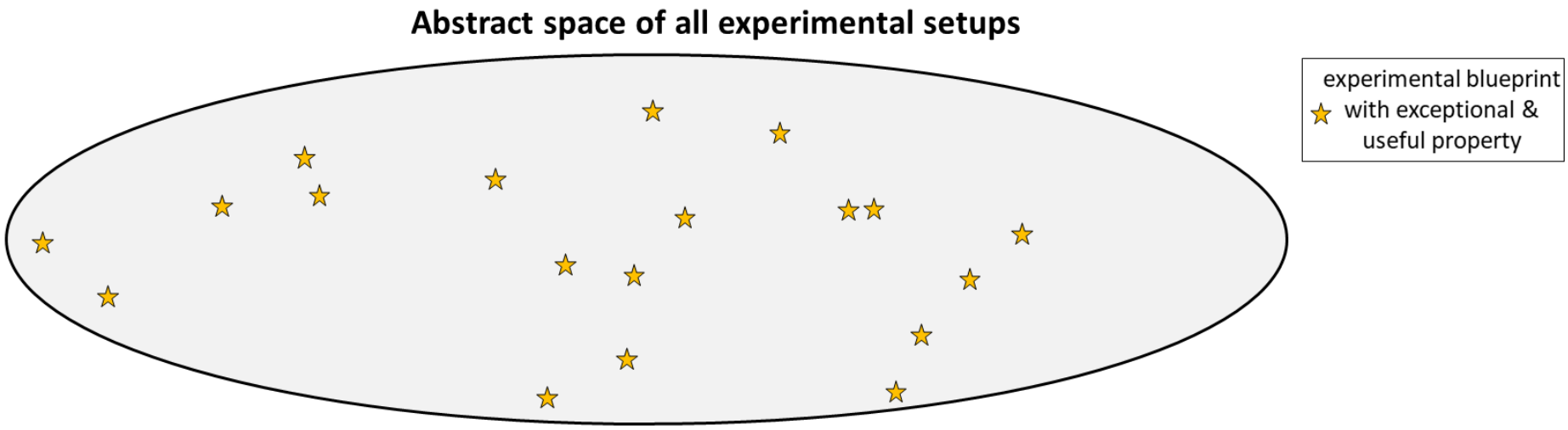
Mario Krenn

Artificial Scientist Lab

@mariokrenn6240

http://mariokrenn.wordpress.com/

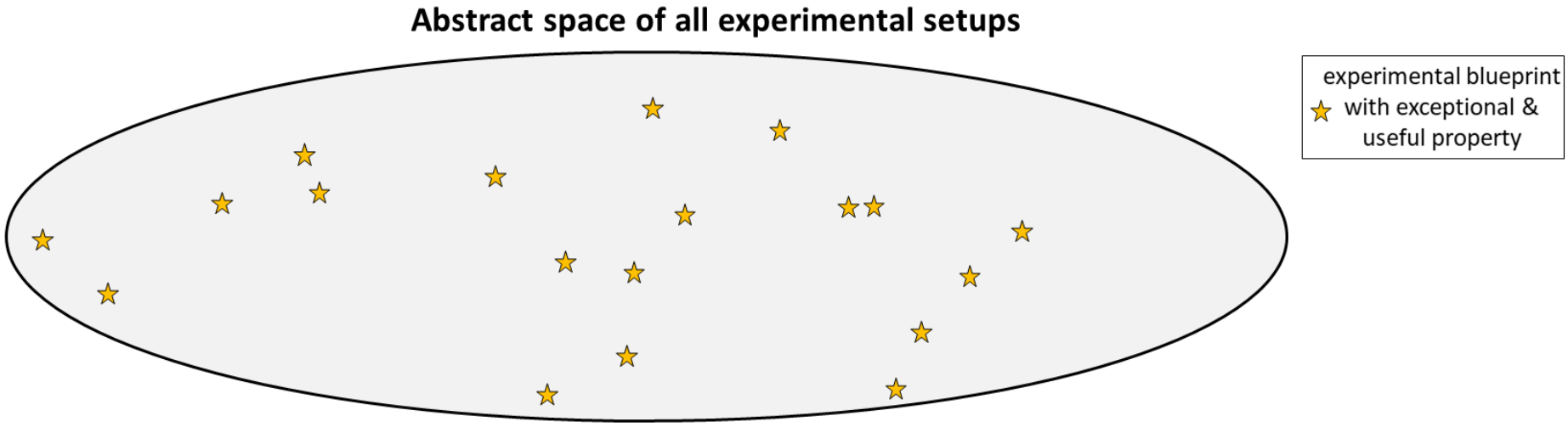
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN


Abstract space of all experimental setups
experimental blueprint
with exceptional &
useful property

Some examples: (without symmetry)

3 lasers, 3 BS, 3 detectors: 1000 combinations

5 lasers, 5 BS, 5 detectors: 81,000 combinations (!)



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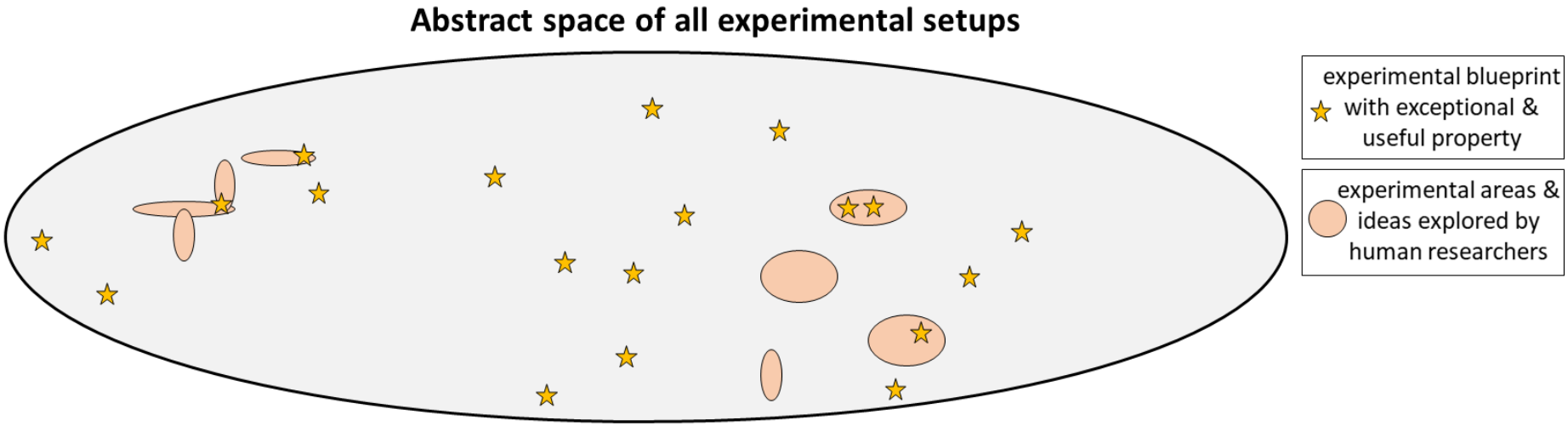

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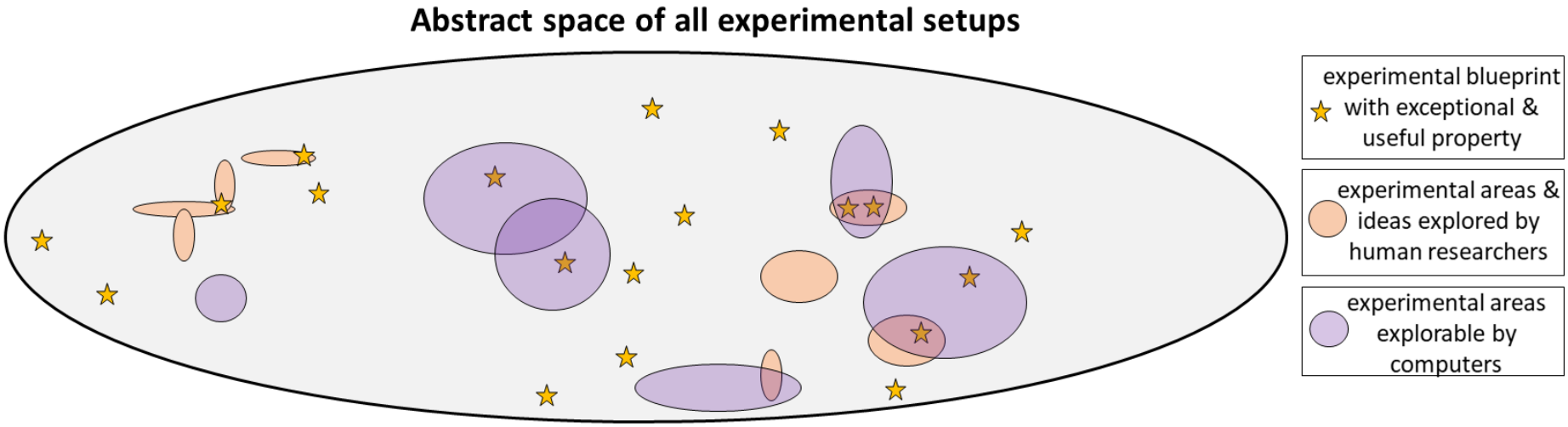
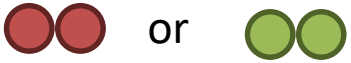


How to design quantum experimental setups?

Quantum Entanglement:

n=2, d=2:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$



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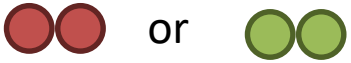

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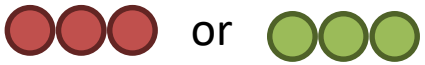

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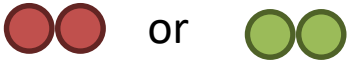

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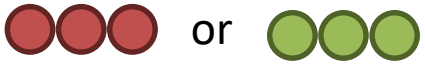

n=2, **d=3**: $|\psi\rangle_{3D} = \frac{1}{\sqrt{3}}(|00\rangle + |11\rangle + |22\rangle)$

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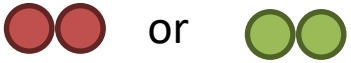

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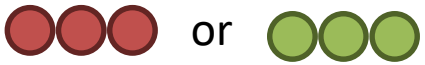

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High-dimensional multipartite entanglement

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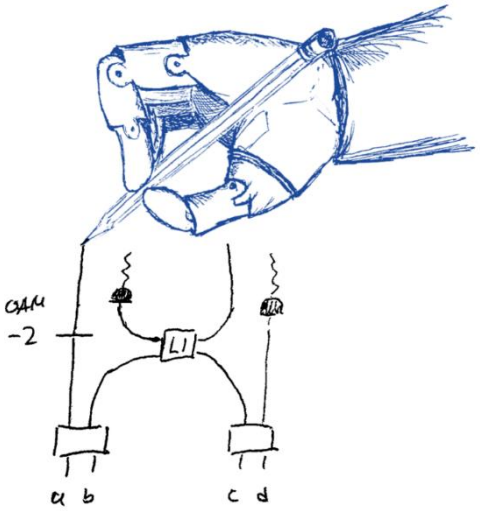

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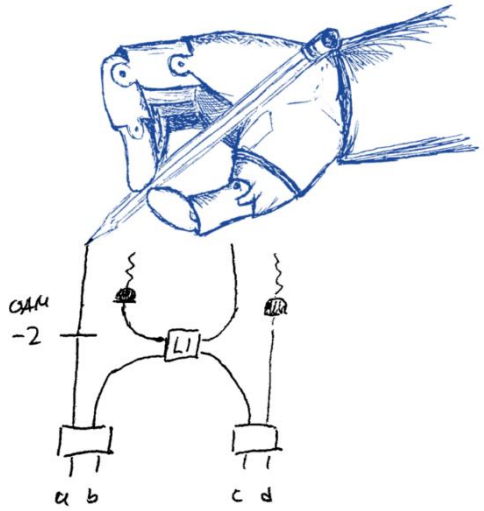

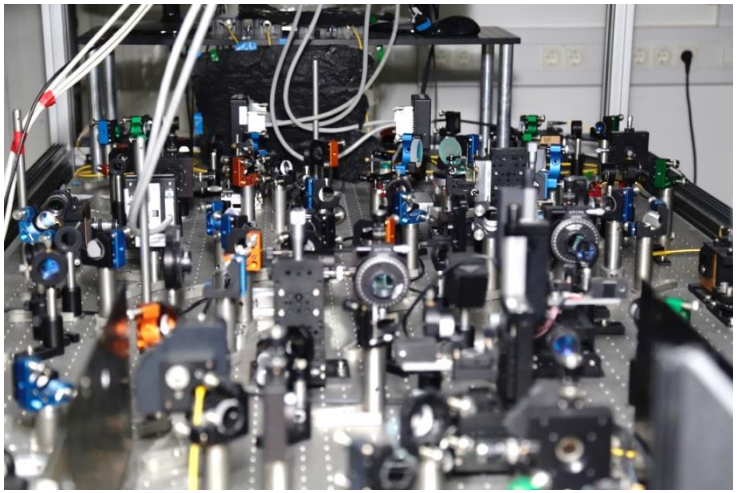

Krenn, Malik, Fickler, Lapkiewicz, Zeilinger, Automated Search for new Quantum Experiments, *Phys. Rev. Lett.* **116**, 090405 (2016)
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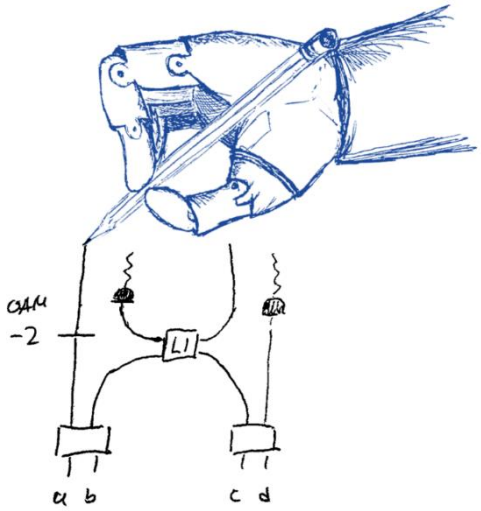

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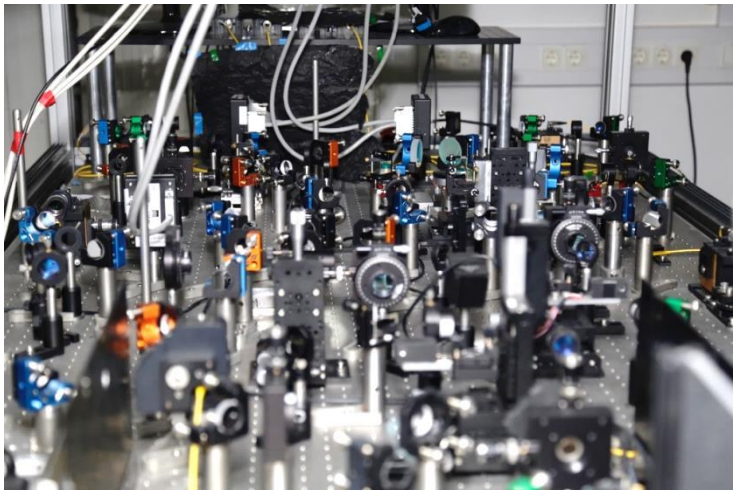

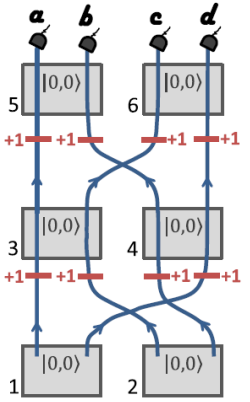

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Computer-inspired ideas and concepts

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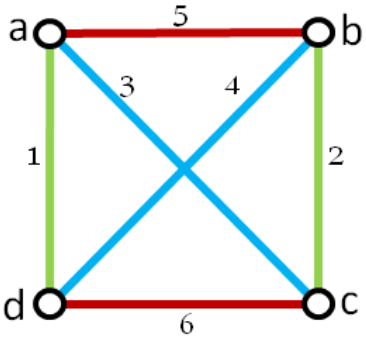
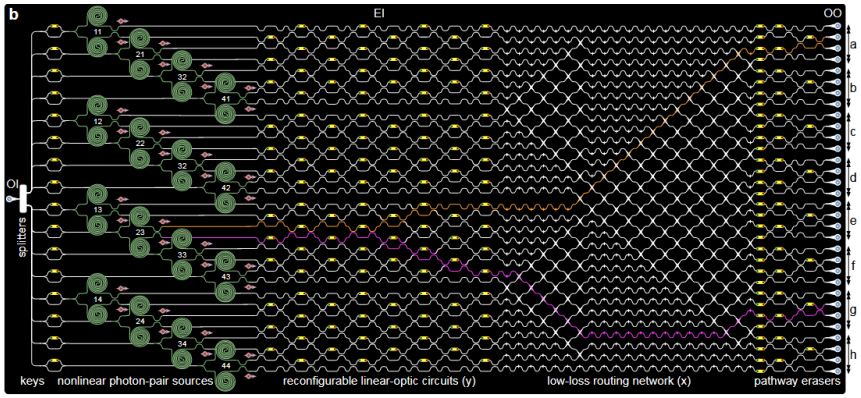
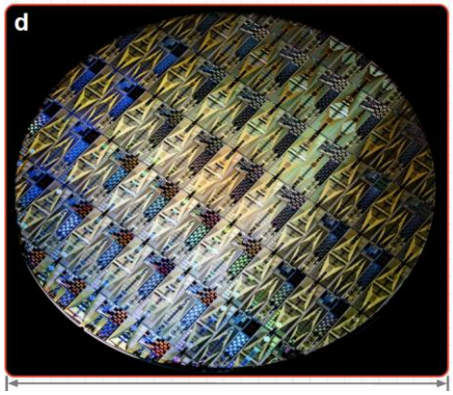
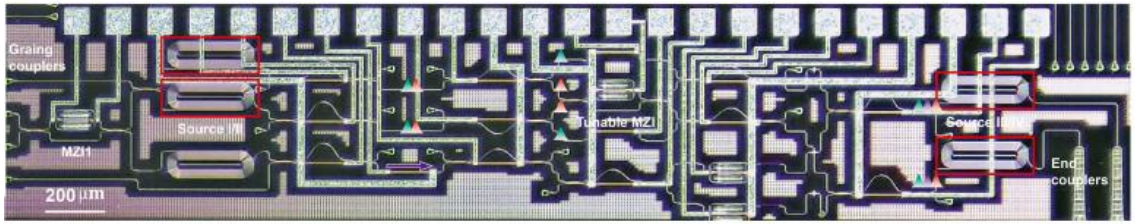


Gu, Erhard, Zeilinger, MK, *PNAS* **116** (2019).

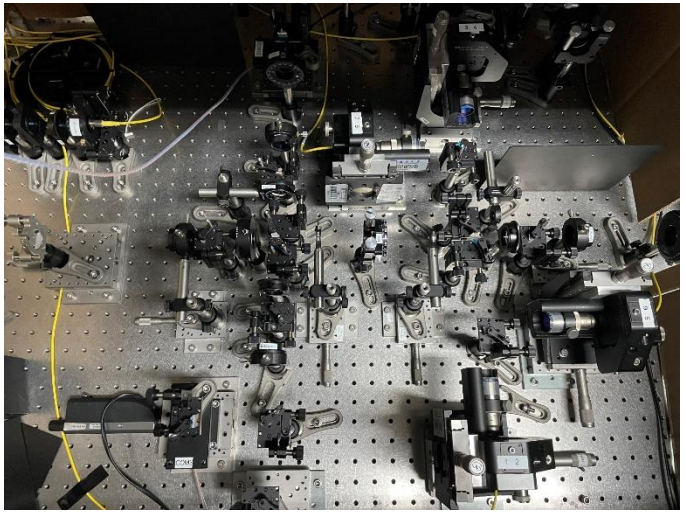
Bao et al., Very-large-scale integrated quantum graph photonics, *Nature Photonics*, **17**, 573 (2023) .







Feng, et al., *On-Chip nonlocal quantum interference between the origins of a four-photon state*, *Optica* (2023).



Qian et al., *Multiphoton non-local quantum interference controlled by an undetected photon*, *Nature Communications* **14** (1), 1480 (2023)

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Perspective

The sounds of science—a symphony for many instruments and voices

Gerianne Alexander[1], Roland E Allen[2], Anthony Atala[3], Warwick P Bowen[4,5], Alan A Coley[6], John B Goodenough[7], Mikhail I Katsnelson[8], Eugene V Koonin[9], Mario Krenn[10,11], Lars S Madsen[5], Martin Månsson[12], Nicolas P Mauranyapin[4], Art I Melvin[10,13], Ernst Rasel[14,15], Linda E Reichl[16], Roman Yampolskiy[17], Philip B Yasskin[18], Anton Zeilinger[10,13] and Suzy Lidström[19,20]

14. How can a computer find autonomously new, surprising or creative solutions or insights? by Mario Krenn, Art I. Melvin and Anton Zeilinger

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Highly efficient computer-designed quantum experiments

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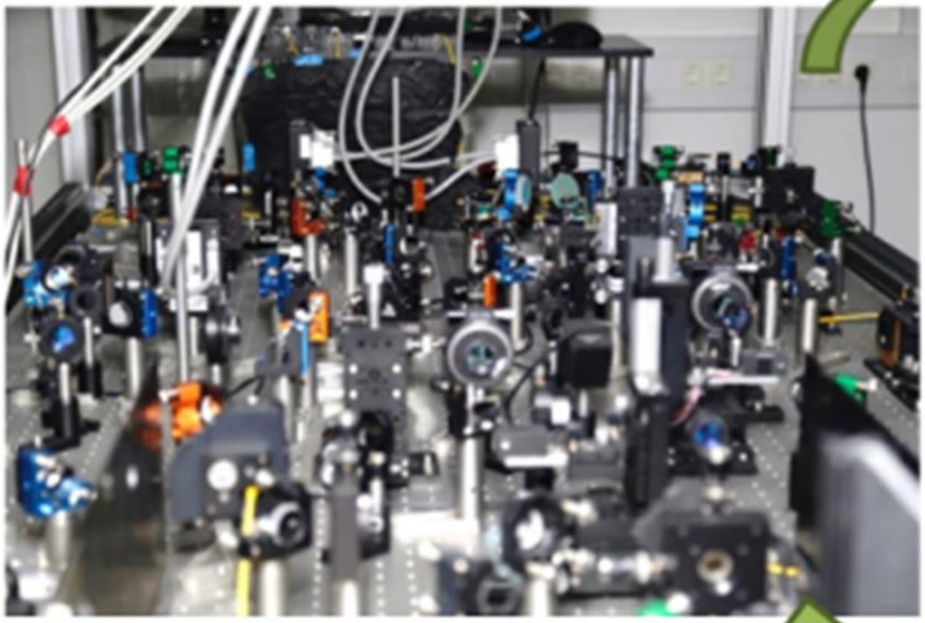
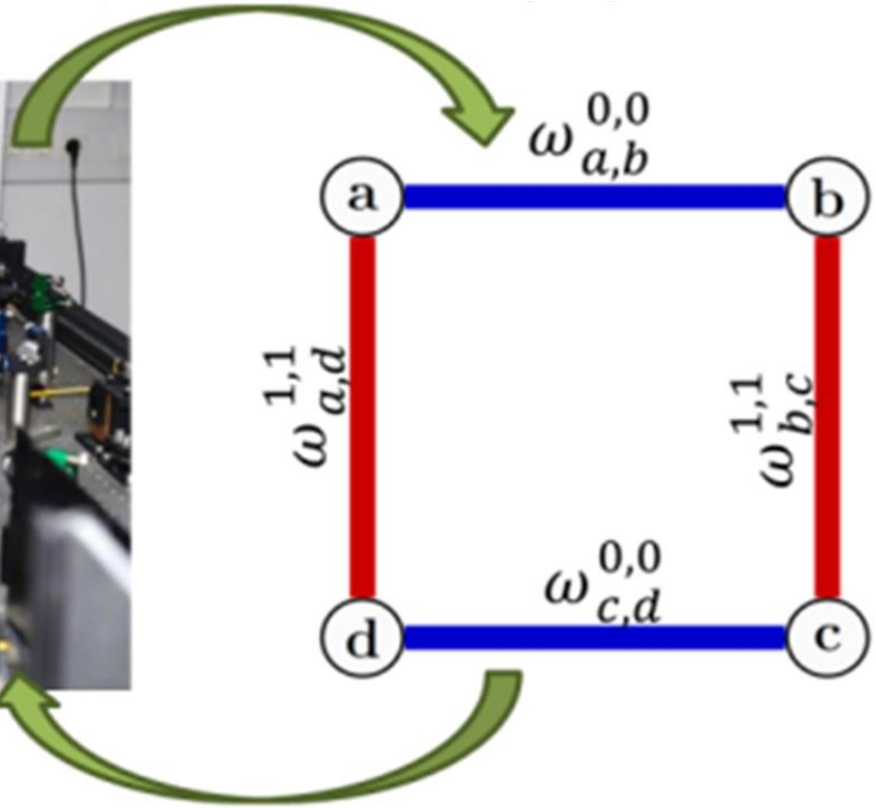
Change Perspective:

New representation -> orders of magnitude speed-up.





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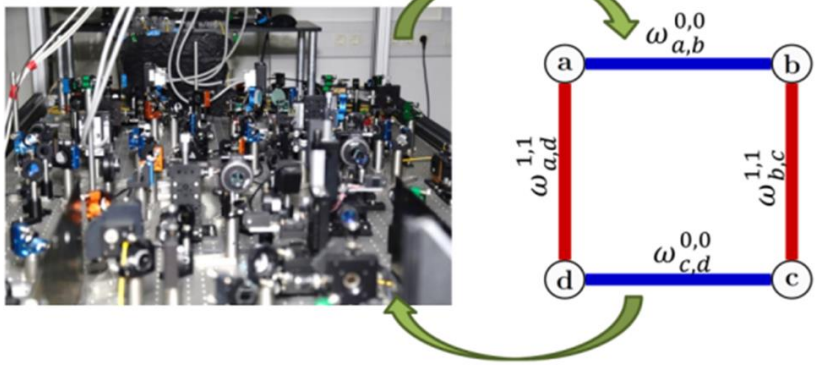
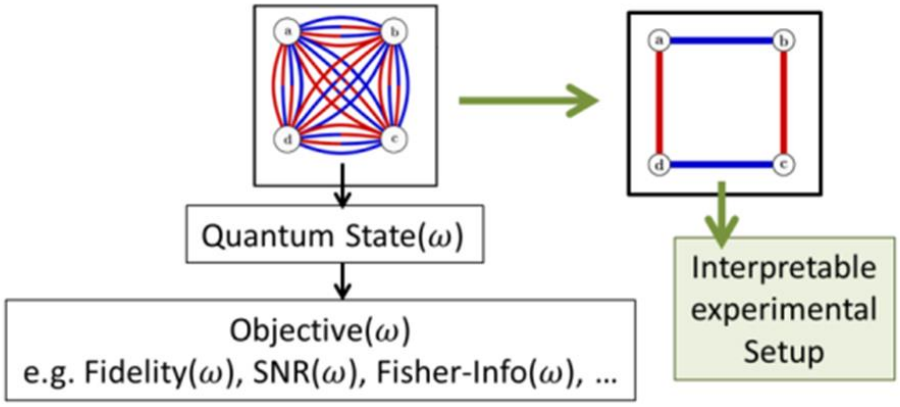
Vertex: Photonic path
Edge: Photon pair
Edge weight: amplitude
Color: Photonic Mode

A) Bridge between quantum experiments and graphs



B) Gradient-based optimization + discrete topological optimization



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Quantum
the open journal for quantum science

Digital Discovery of 100 diverse Quantum Experiments with PyTheus

Carlos Ruiz-Gonzalez[§1], Sören Arlt[§1], Jan Petermann[1], Sharareh Sayyad[1], Tareq Jaouni[2], Ebrahim Karimi[1,2], Nora Tischler[3], Xuemei Gu[1], and Mario Krenn[1]

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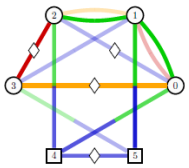

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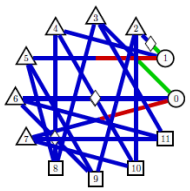
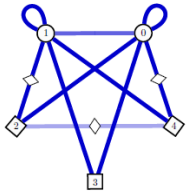
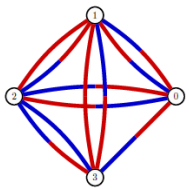


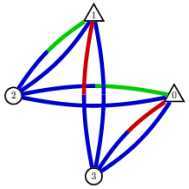
(b) Heralded 3D Bell state with single photons (improves state-of-the-art design by requiring less ancilla photons)



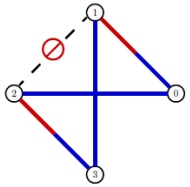
(c) Two-mode five-photon N00N state $|50\rangle + |05\rangle$ (very symmetric shape with an inscribed pentagram)



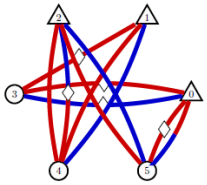
(d) A 4-qubit entangled states with unit coefficients, which requires complex-valued weights for generation



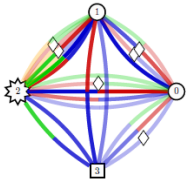
(e) Quantum measurement for a quantum communication task with quantum advantage (Mean King's Problem)



(f) Entanglement swapping without using two Bell states



(g) Toffoli quantum gate without ancilla photons



(h) Mixed state with bound entanglement that can violate a Bell inequality (counterexample to the Peres conjecture from 1999, solved 2014)

github.com/artificial-scientist-lab/PyTheus

`pip install pytheusQ`

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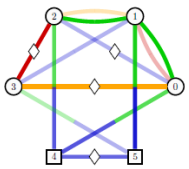

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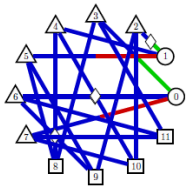

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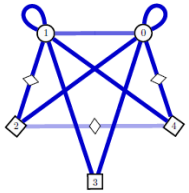

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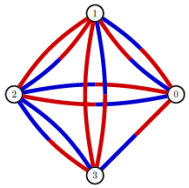

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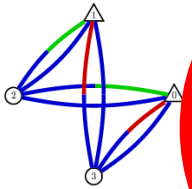

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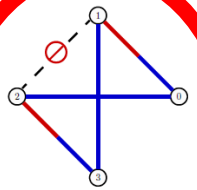
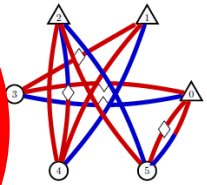
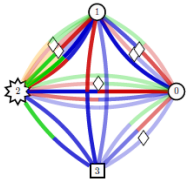


(f) Entanglement swapping without using two Bell states



(g) Toffoli quantum gate without ancilla photons



(h) Mixed state with bound entanglement that can violate a Bell inequality (counterexample to the Peres conjecture from 1999, solved 2014)

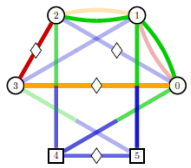
Highly efficient computer-designed quantum experiments

Quantum
the open journal for quantum science

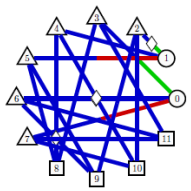
Digital Discovery of 100 diverse Quantum Experiments with PyTheus

Carlos Ruiz-Gonzalez[§1], S
Ebrahim Karimi[1,2], Nora

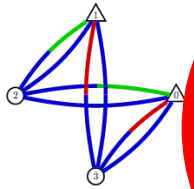
Quantum 7, 1204 (2(



(a) Four-dimensional four-photon GHZ state (overcoming the 3-dimensional barrier for multiphoton entanglement)



(b) Heralded 3D Bell state with single photons (improves state-of-the-art design by requiring less ancilla photons)



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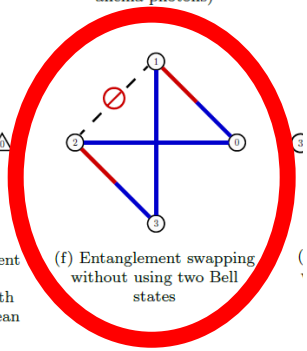

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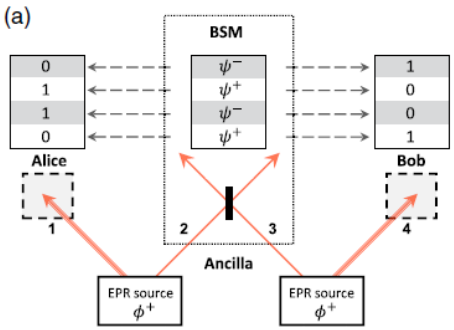
PHYSICAL REVIEW LETTERS **133,** 233601 (2024)

Entangling Independent Particles by Path Identity

Kai Wang,[1,‡] Zhaohua Hou,[1,‡] Kaiyi Qian,[1] Leizhen Chen,[1] Mario Krenn,[2,*] Shining Zhu,[1] and Xiao-Song Ma[1,†]
[1]*National Laboratory of Solid-state Microstructures, School of Physics, Collaborative Innovation Center of Advanced Microstructures, Jiangsu Physical Science Research Center, Nanjing University, Nanjing 210093, China*
[2]*Max Planck Institute for the Science of Light (MPL), Erlangen, Germany*



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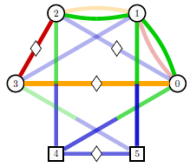

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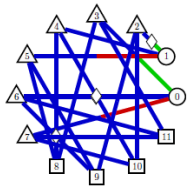

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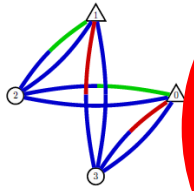

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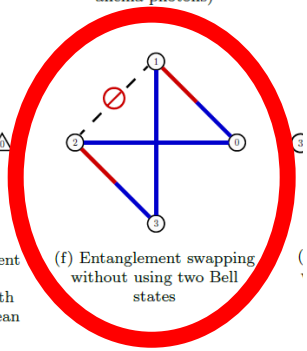

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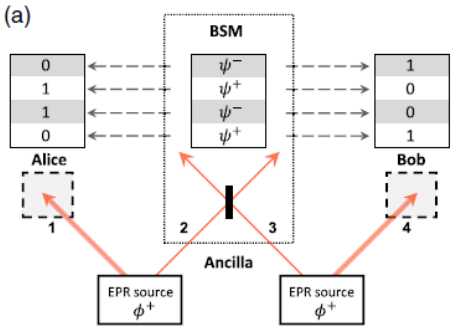
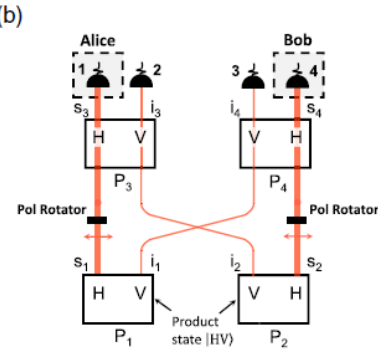


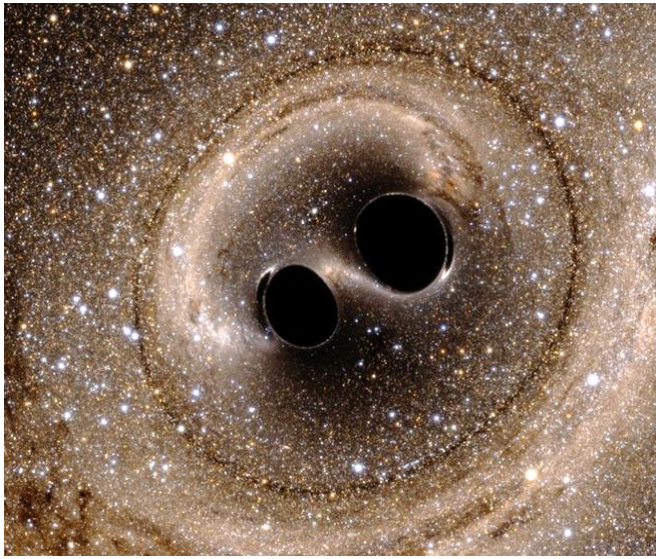


Mario Krenn

AI-driven design of new Gravitational Wave Detectors

with Yehonathan Drori, Rana X. Adhikari (Caltech, LIGO)

Phys. Rev. X **15**, 021012 (2025)



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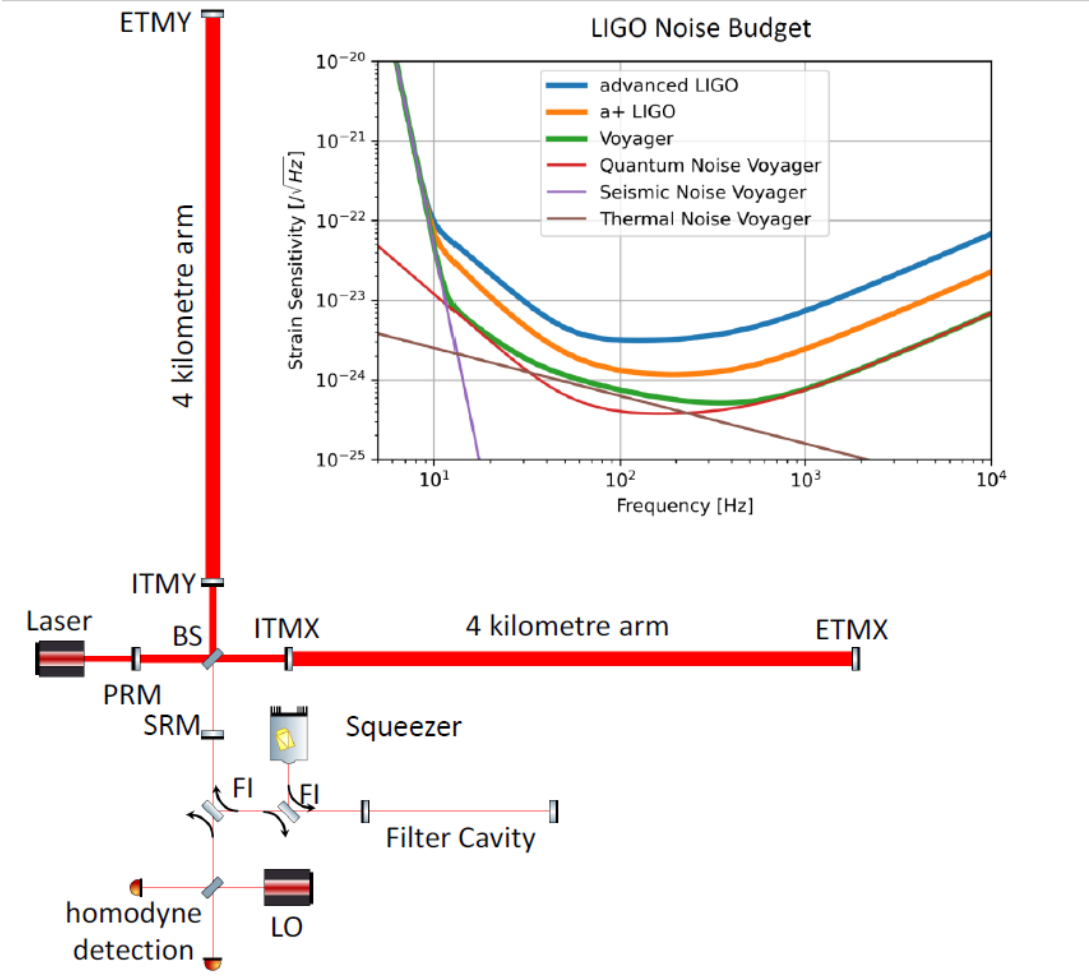
LIGO's next Generation Detector Update: Voyager



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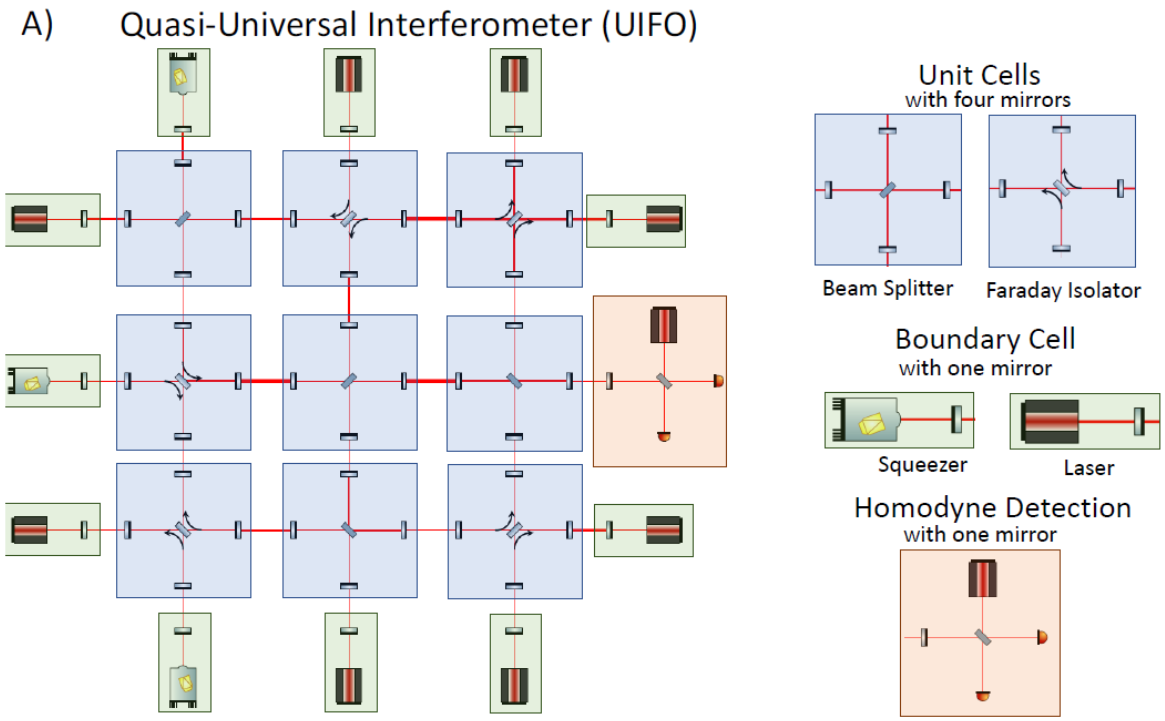

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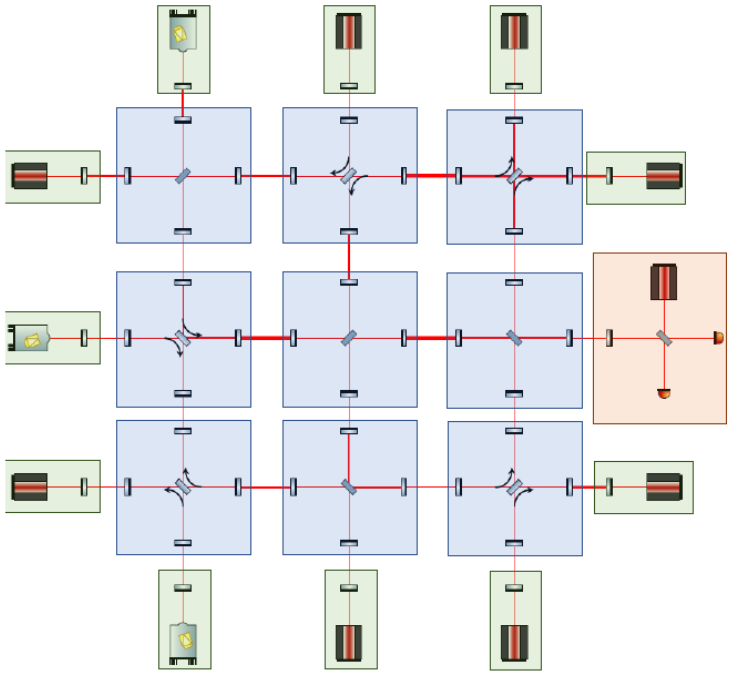
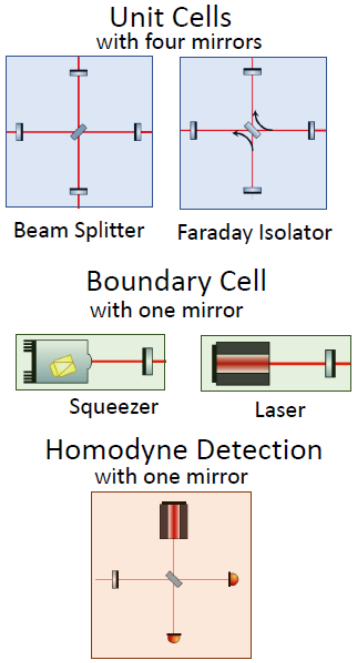
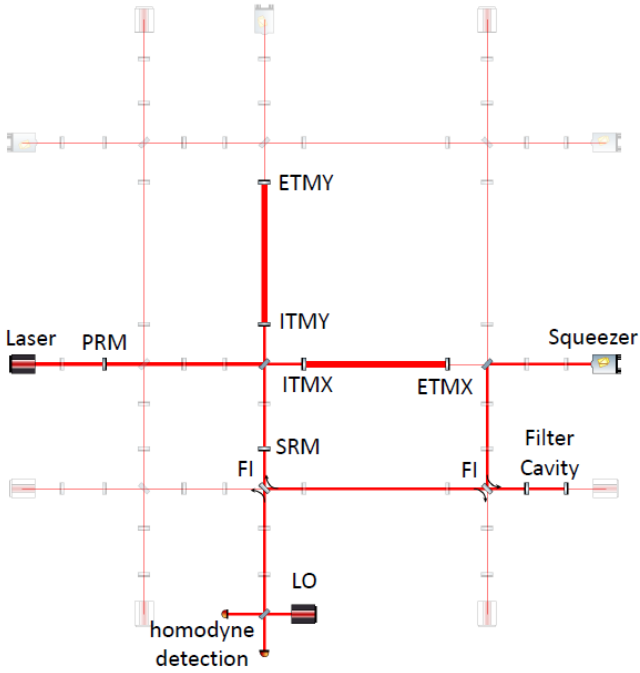
Phys. Rev. X **15**, 021012 (2025)

A) Quasi-Universal Interferometer (UIFO)





B) LIGO Voyager in UIFO



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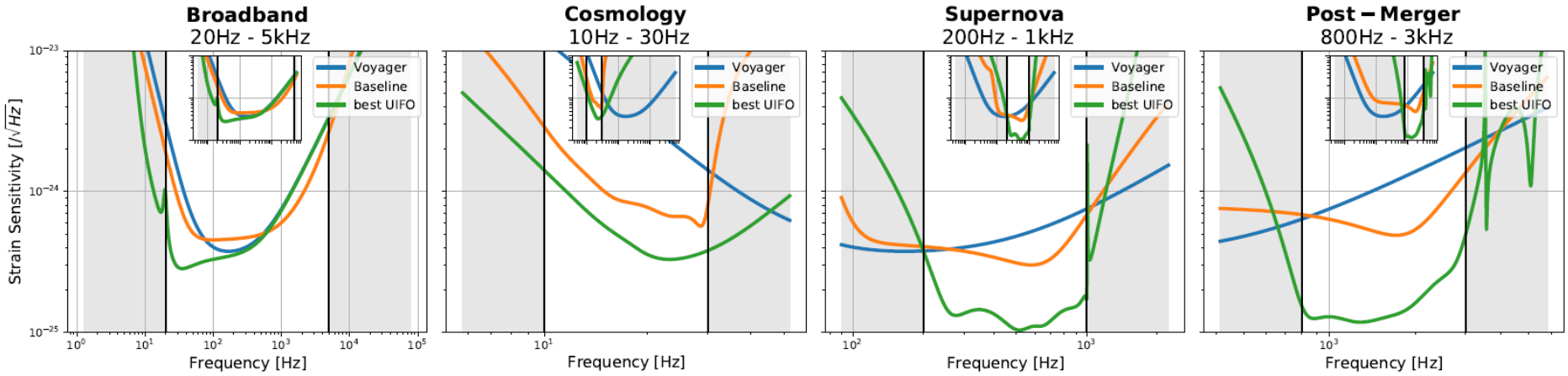

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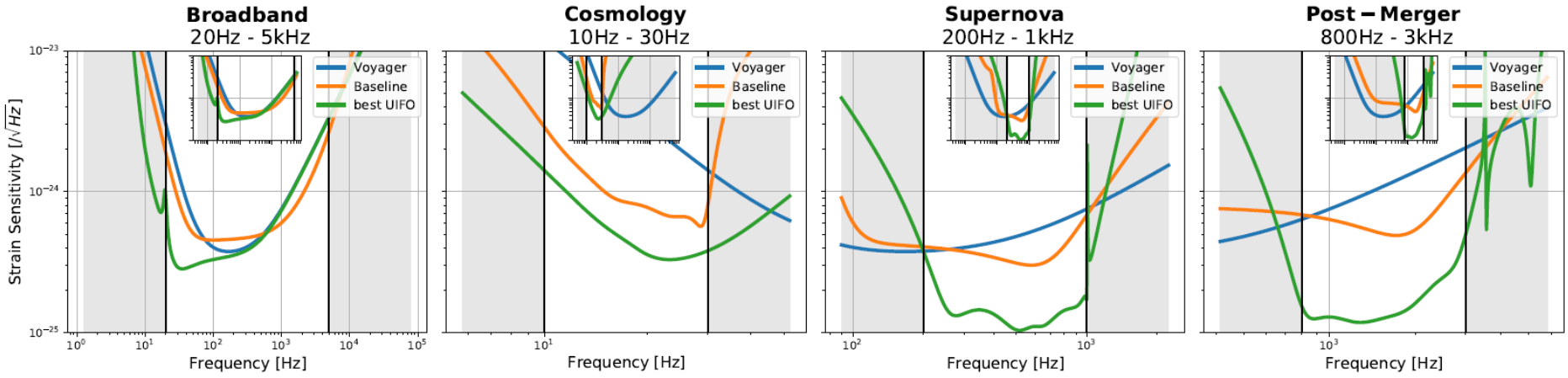

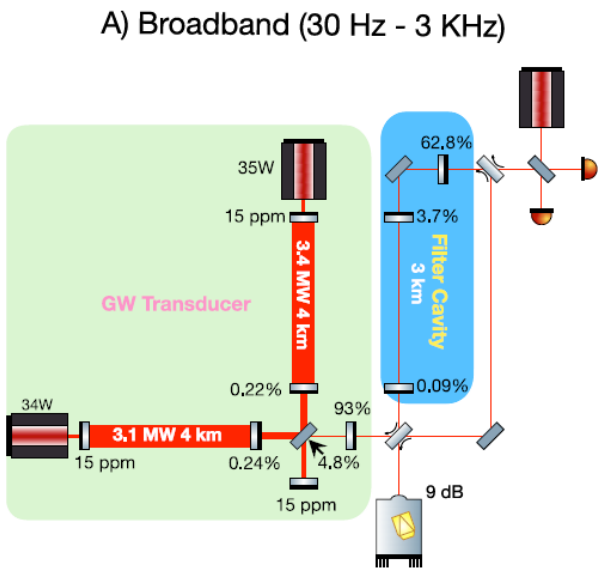

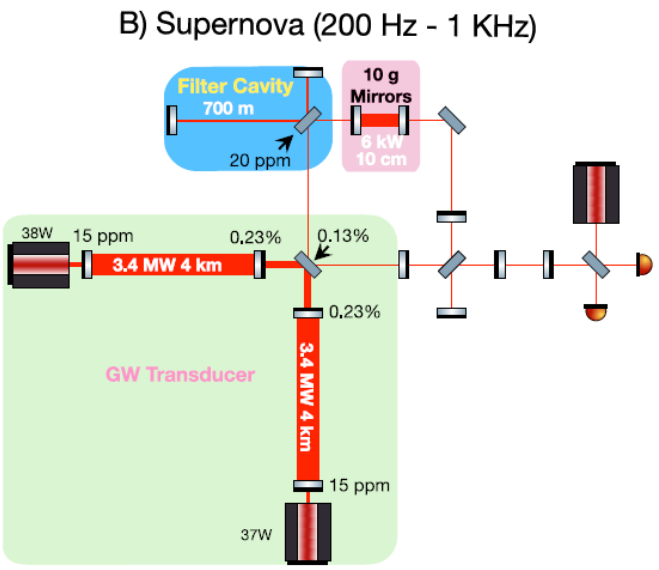

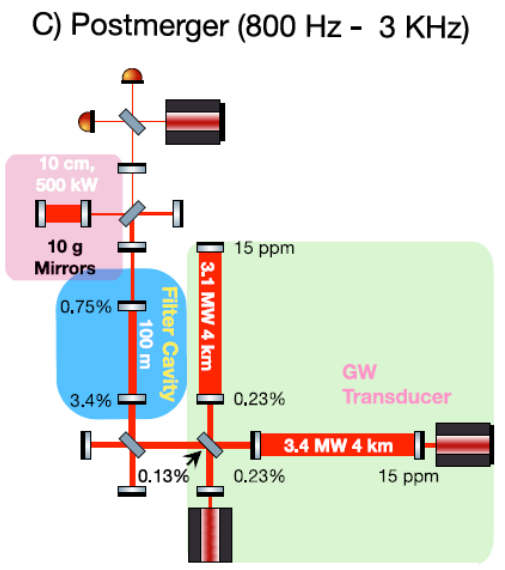

A Differentiable Interferometer Simulator for the Computational Design of Gravitational Wave Detectors

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

Second EuCAIFCon on June 17, 2025

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TÜBINGEN

MAX PLANCK INSTITUTE
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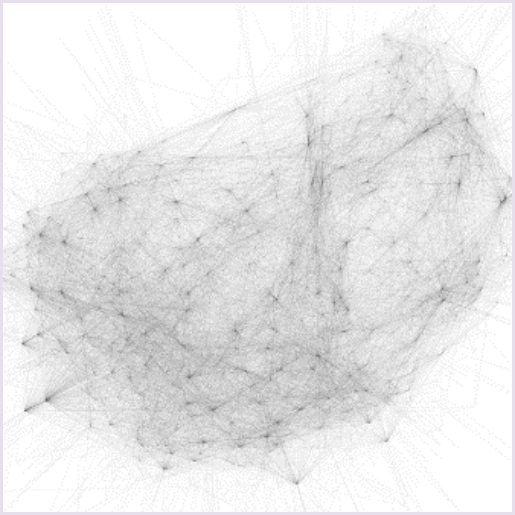
LIGO

From Large Collection Of Literature



Semantic Network of QM from 750k papers

Vertices: Concepts
Edges: Co-Occurance

Krenn, Zeilinger, *PNAS* **117**, 1910 (2020)
Krenn et al., *Nat. Mach. Intell.* (2023)

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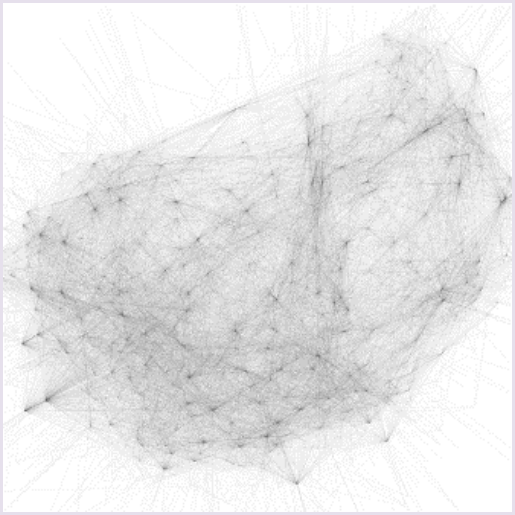

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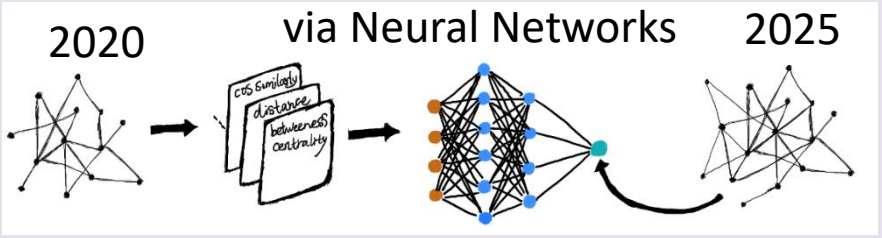
Link Prediction via Neural Networks



Then: From 2025 to 2030!

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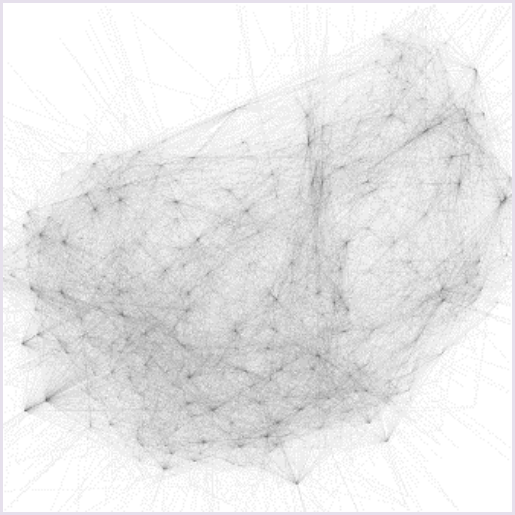

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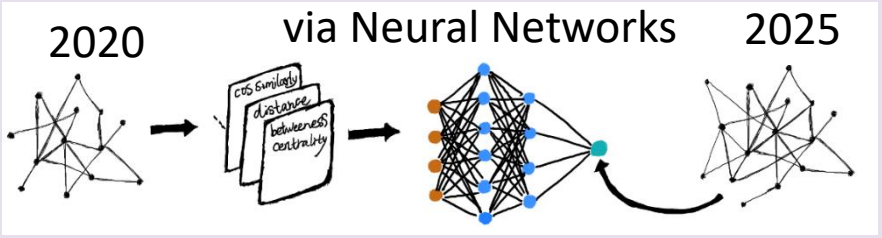

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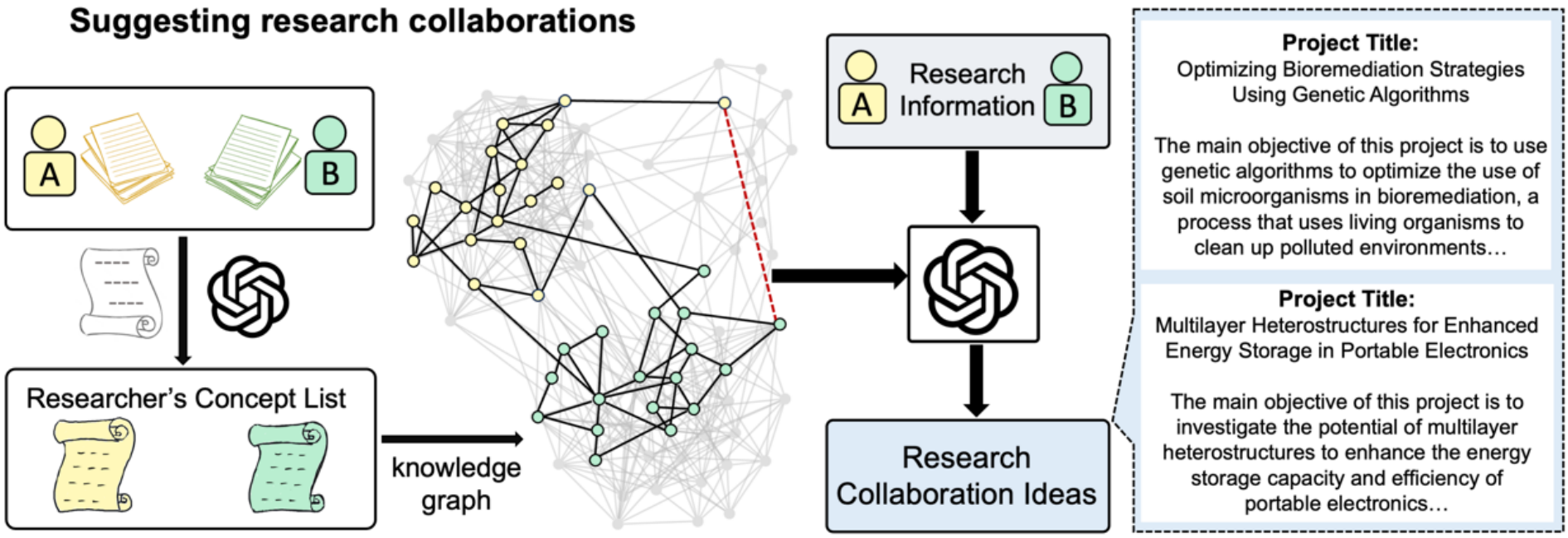

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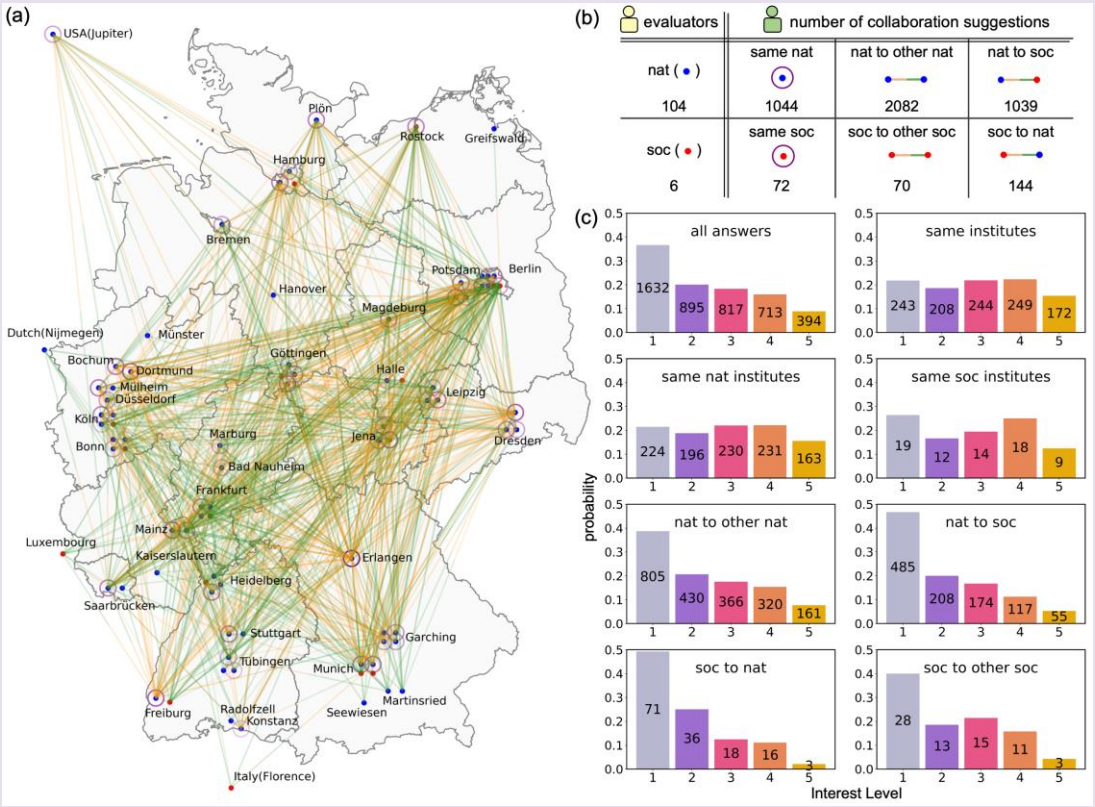

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Conclusion

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In many domains in physics (*quantum optics, gravitational wave physics, microscopes/telescopes soon*), we have now algorithms for

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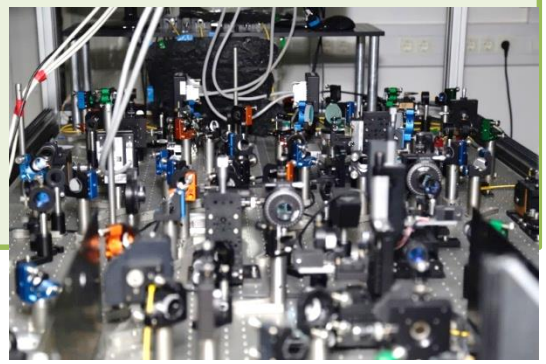
The solutions are presented such that

we can learn and understand new concepts.



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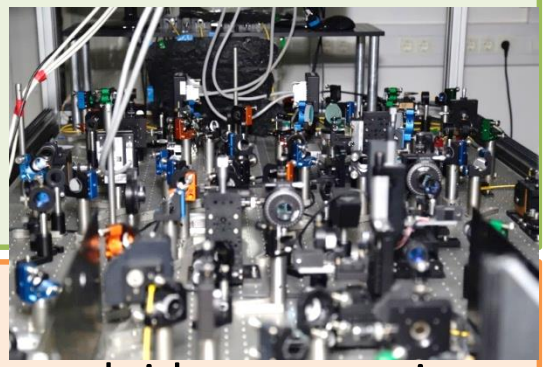

Automated Idea Generation:

Towards personalized, new, high-impact, interesting research idea generation

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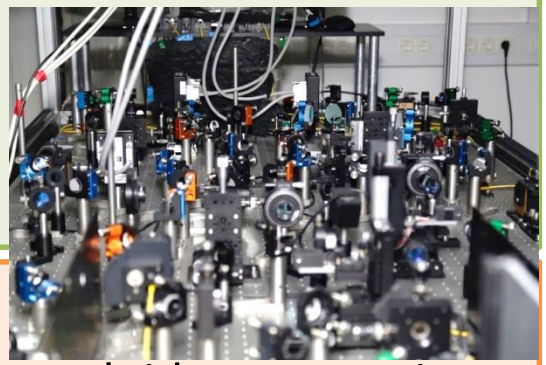

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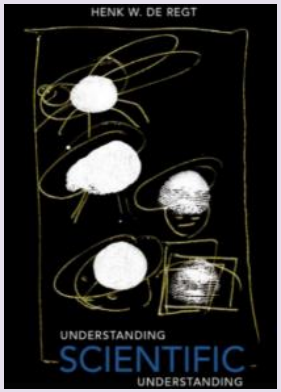
Artificial Scientists

Creativity?

Curiosity?

(a) learn to explore on Level-1 (b) explore faster on Level-2

Understanding?



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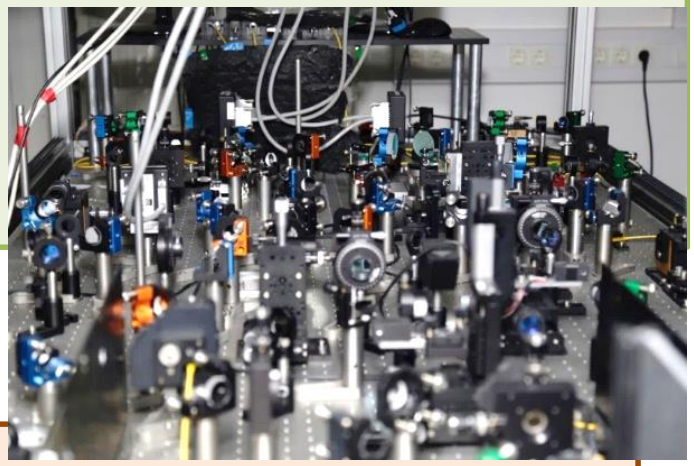

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