TU WIEN Informatics

Introduction to Computational Sustainability

Ivona Brandić

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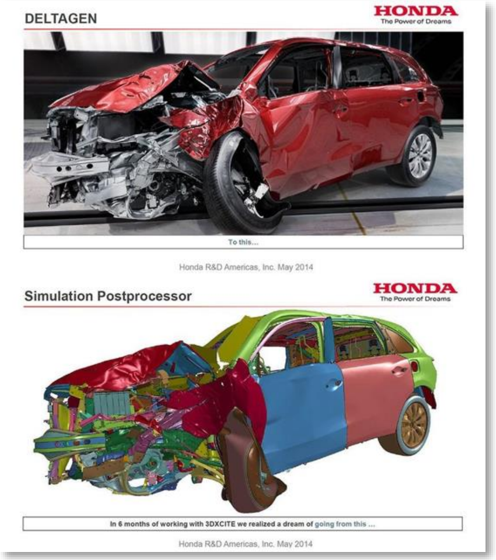
TU Wien

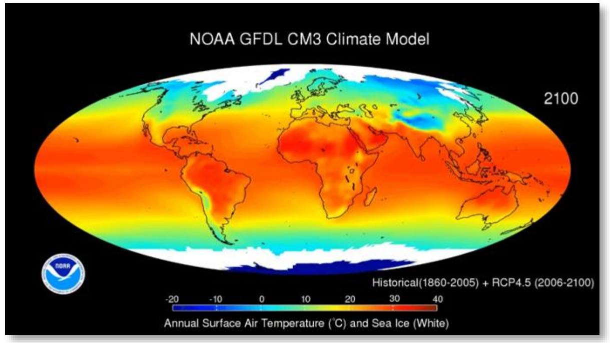
ivona.brandic@tuwien.ac.at

Computational Power

Simulation

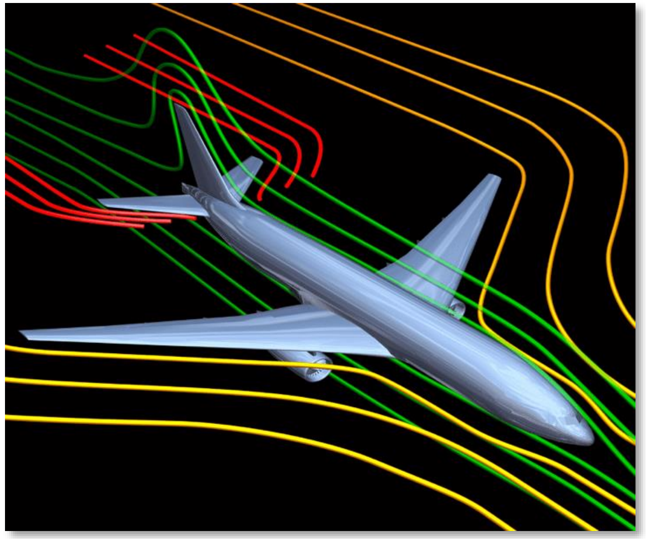


Mechanical Structure Simulation

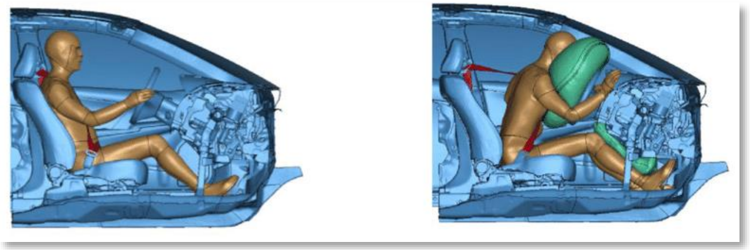


Climate Prediction

Optimization

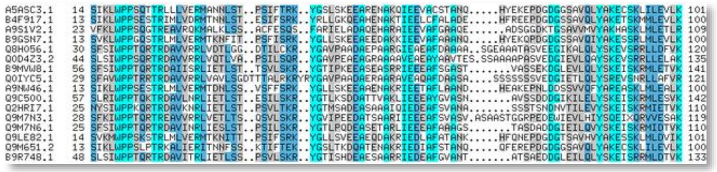


Airflow Optimization



Finite Element Simulation
Hyper Parameter Optimization

Today: Analytics, AI, LLMs,…

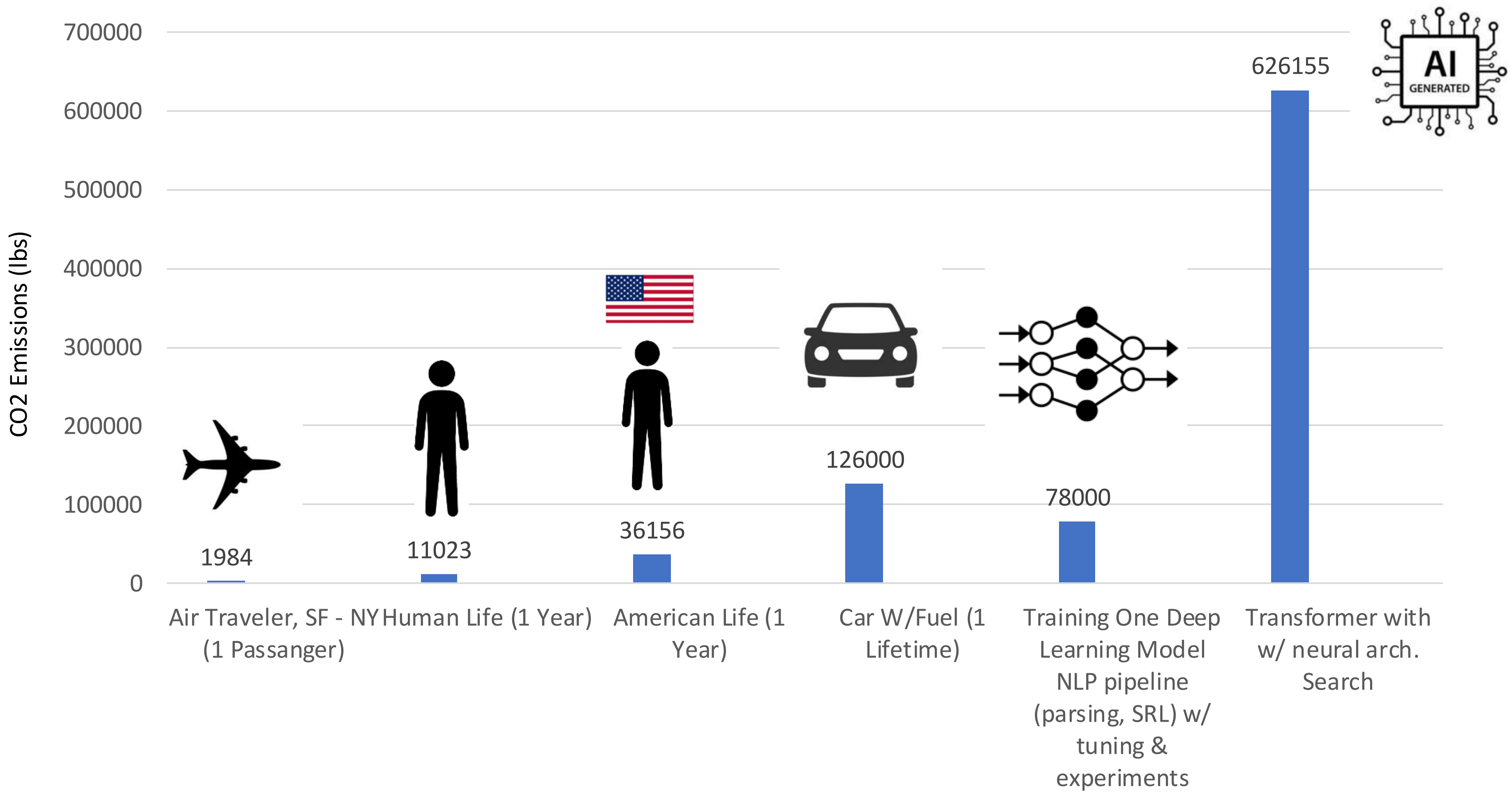


DNA Sequence Analysis
(e.g., Genomic sequencing of SARS-CoV-2)

Large Language Models

Recommendation Engines

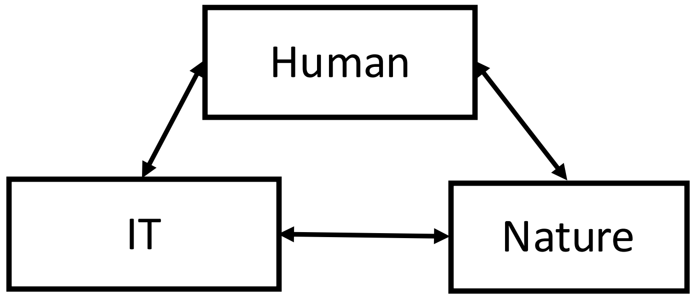
Problem: CO_2 Footprint of (generative) AI



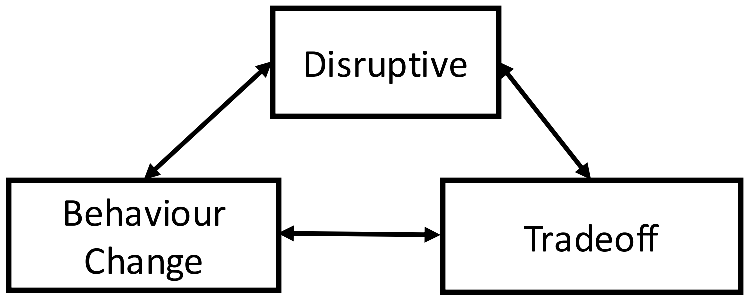
Source: Emma Strubell, Ananya Ganesh, Andrew McCallum: Energy and Policy Considerations for Deep Learning in NLP, ACL (1) 2019: 3645-3650
Inspiration for Visualisation: Keren Bergman, Multicore World 2023 https://2019multicoreworld.files.wordpress.com/2023/02/bergman-keren-23.pdf

Computational Sustainability

Actors:



Methods:



Computational Sustainability

Actors:

Human

IT

Nature

chist-era

Sustainable Watershed Management Through IoT-Driven Artificial Intelligence

FFG Forschung wirkt.

Virtual Shepherd

TRUST! Explaining the increasing energy consumption of IT infrastructures

Methods:

Disruptive

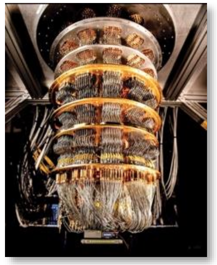
Behaviour Change

Tradeoff

HPQC HIGH-PERFORMANCE QUANTUM COMPUTING

FFG Forschung wirkt.

High Performance Integrated Quantum Computing



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Quantum Algorithm Enginering COMET Module

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ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

WWTF

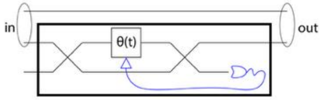
WWTF: AI-supported Holographic Environmental Water Monitoring

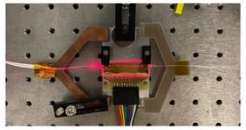
FWF

Themis: Trustworthy and Sustaianble Code Offloading

FWF

Triton: Transprecise Edge

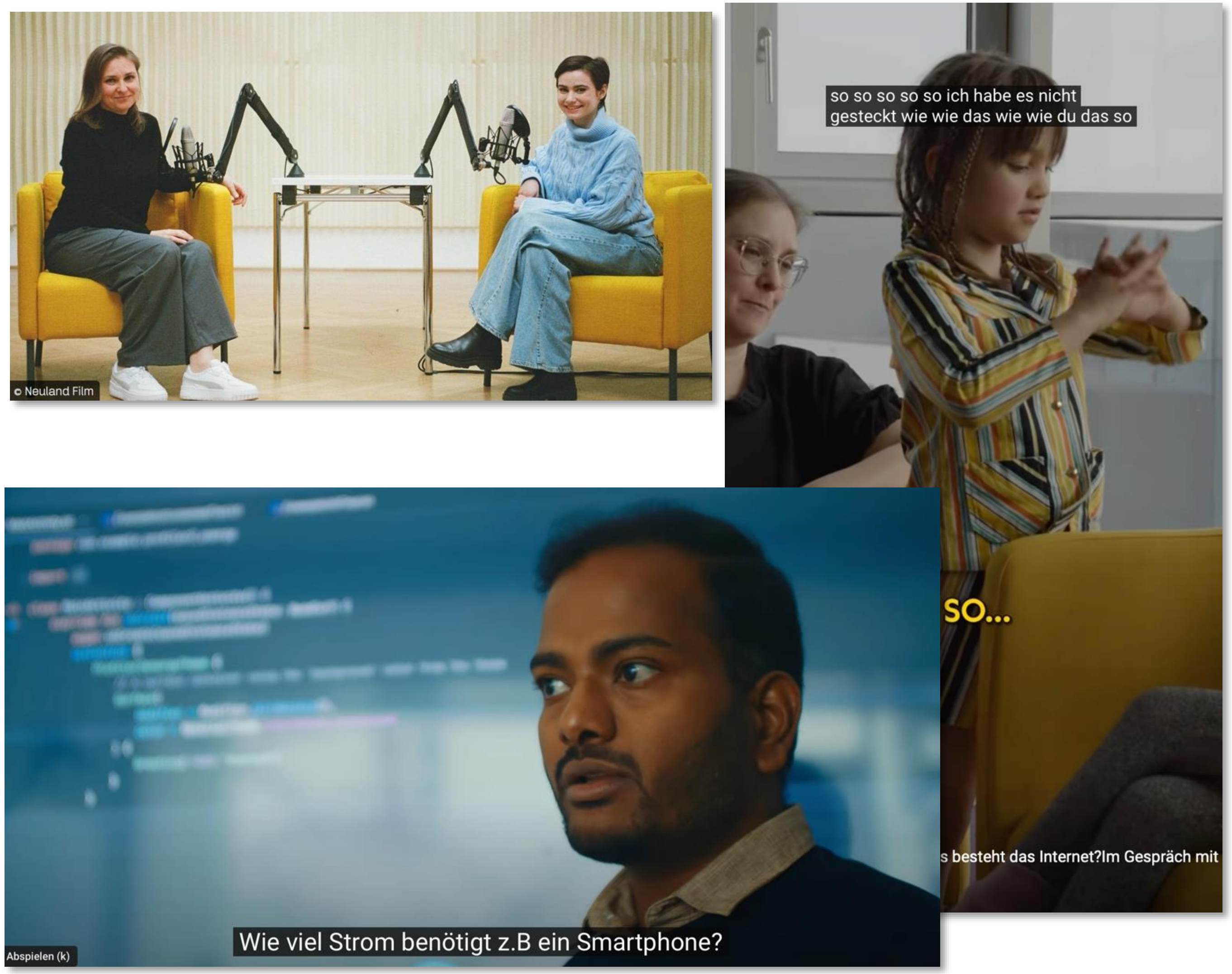




WWTF

WWTF: Advancing learning paradigms for photonic quantum processors

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN



Asking ChatGPT Qs with 5-50 prompts[1]	≈		500ml of water
Search on LLM vs Google Search[1]	≈		2.9 Wh/ Search or up to 20x expensive
A text-to-image generation[2] (1000 inferences)	≈		3 kWh or 3hr of dishwasher
1 min video (e.g., midjourney)	≈		5,4 kWh or 36hr playing Playstation 4.0

Sources: https://www.youtube.com/watch?v=N4Ec_POLtes
https://www.youtube.com/shorts/O6QeeA6jbS0

Costs of saying ”thank you”

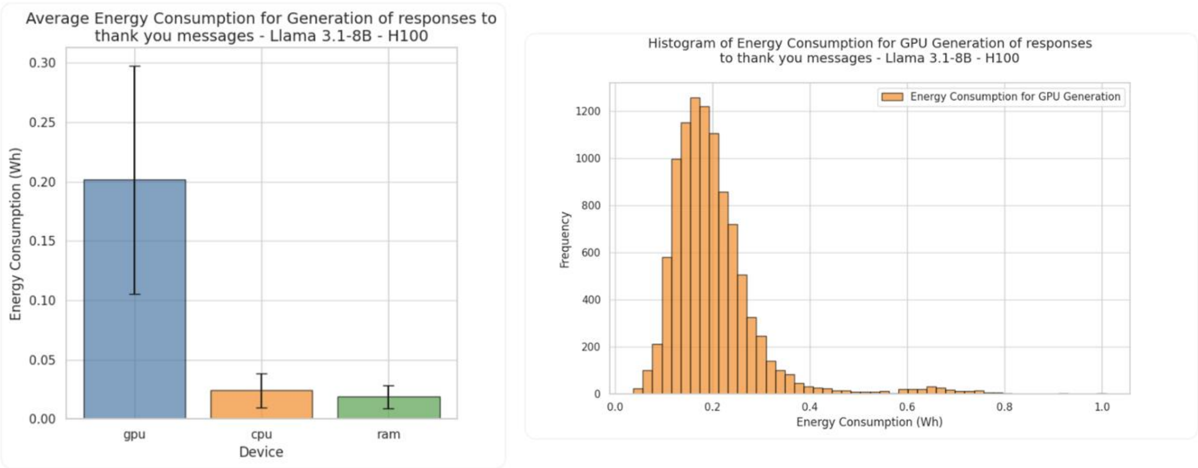


Figure 2: Left — Mean Energy consumption by device (GPU, CPU, RAM) for one response. Right — Histogram of GPU energy to respond to a thank you message.

Source: Saying Thank You to a LLM Isn't Free — Measuring the Energy Cost of Politeness
https://huggingface.co/blog/jdelavande/thank-you-energy

Wie viel kostet uns die Höflichkeit mit ChatGPT, ORF1 ZIB Interview.

Human-AI Interaction for Sustainability (HAI4S): Green Prompting Strategies and Eco-Feedback for Efficient Use of Large Language Models

Hosting Institution: *LIT Robopsychology Lab* JKU

Supervisors:

Martina Mara
JKU

Ivona Brandic
TU Wien

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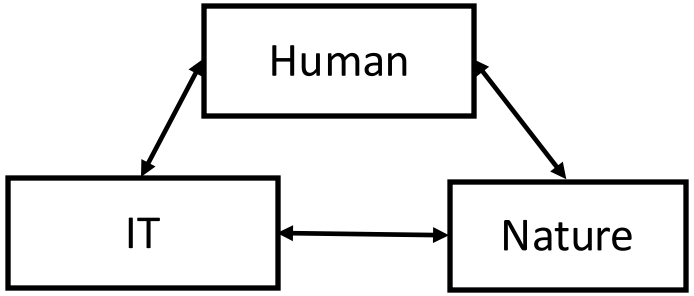
Computational Sustainability

Actors:



Sustainable Watershed Management Through IoT-Driven Artificial Intelligence

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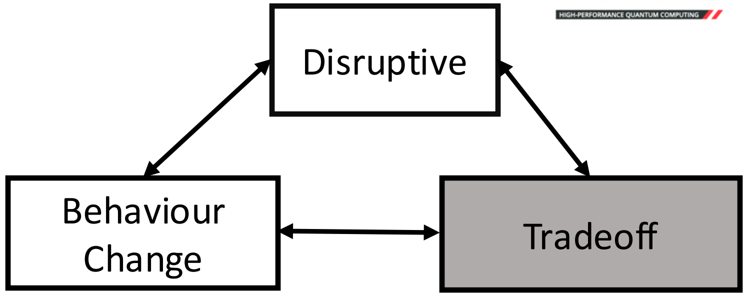
Methods:



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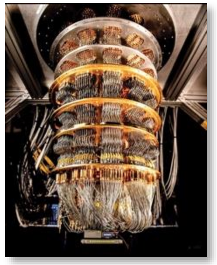
High Performance Integrated Quantum Computing



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W|W|T|F

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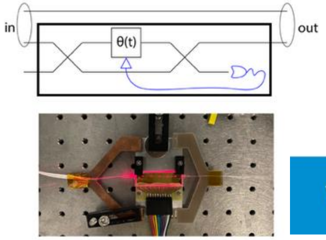
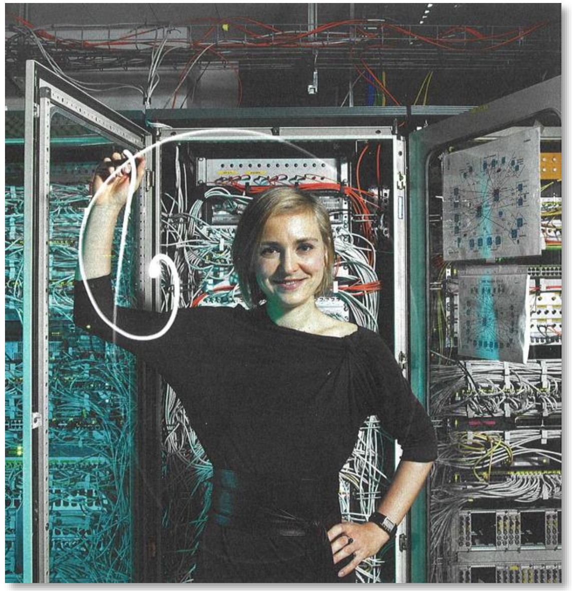


W|W|T|F

WWTF: Advancing learning paradigms for photonic quantum processors

Data Centers once…

INRIA Rennes, 2012



TU Wien (VCS), 2011 ("Der Falter")

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

IRIT
Institut de Recherche
en Informatique de Toulouse
CNRS - INP - UT3 - UT1 - UT2J

FALTER

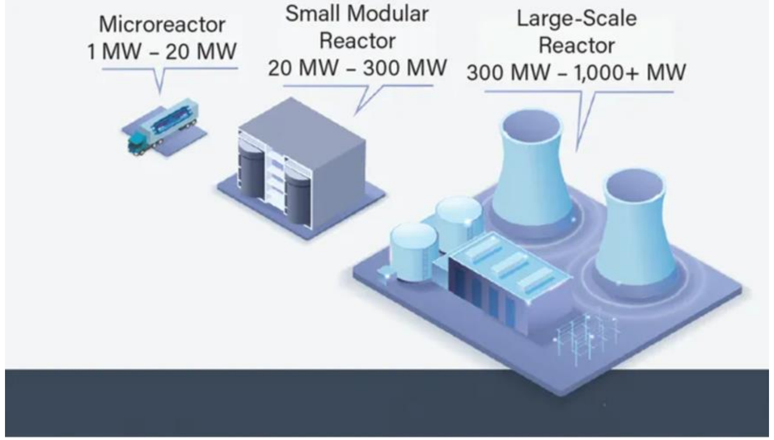
lrz Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

SuperMUC Munich, 2013

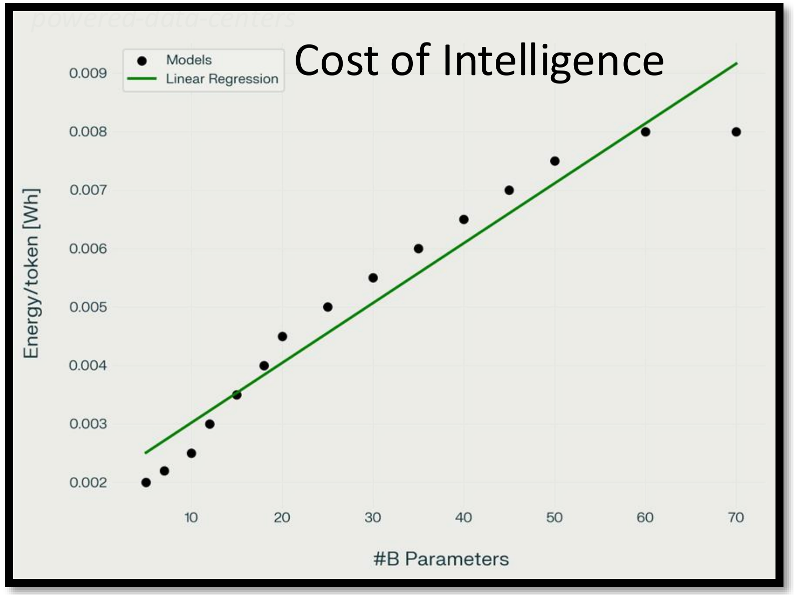
TU Wien, 2018

TU WIEN

… Data Centers Now



Source: https://www.datacenterknowledge.com/energy-power-supply/going-nuclear-a-guide-to-smrs-and-nuclear-powered-data-centers



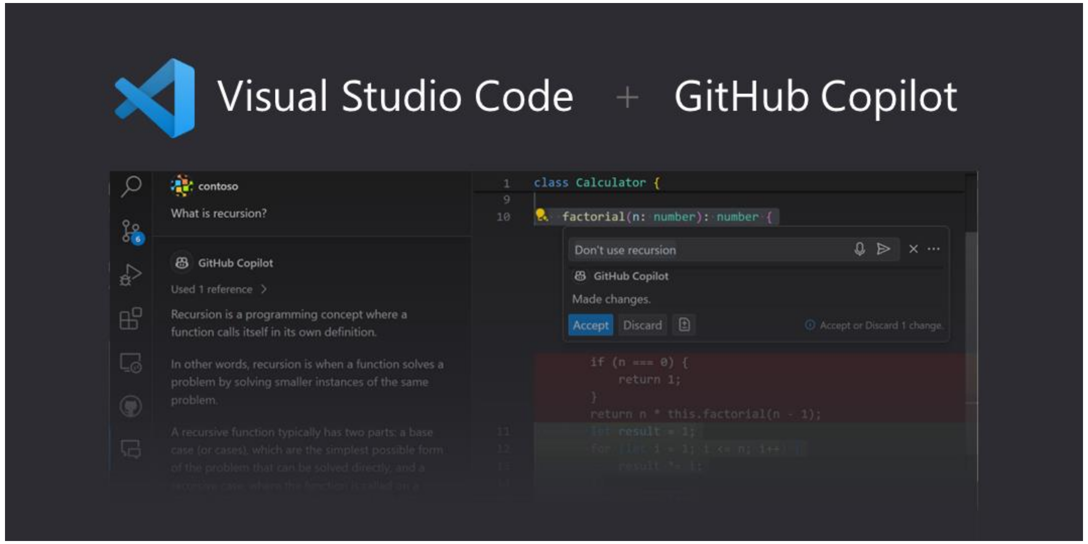
Source: https://www.datacenterdynamics.com/en/news/amazon-signs-deals-to-invest-in-nuclear-smrs-to-power-data-centers/

Code generation

- AI-native IDEs are seeing rapid adoption, tailored for LLM-based code assistants.

- Code assistants are widely viewed as the future of software development.

- Studies report that 30–40% of code in large organizations is now AI-generated[1].



1. McKinsey & Company, *The Economic Potential of Generative AI*, 2023

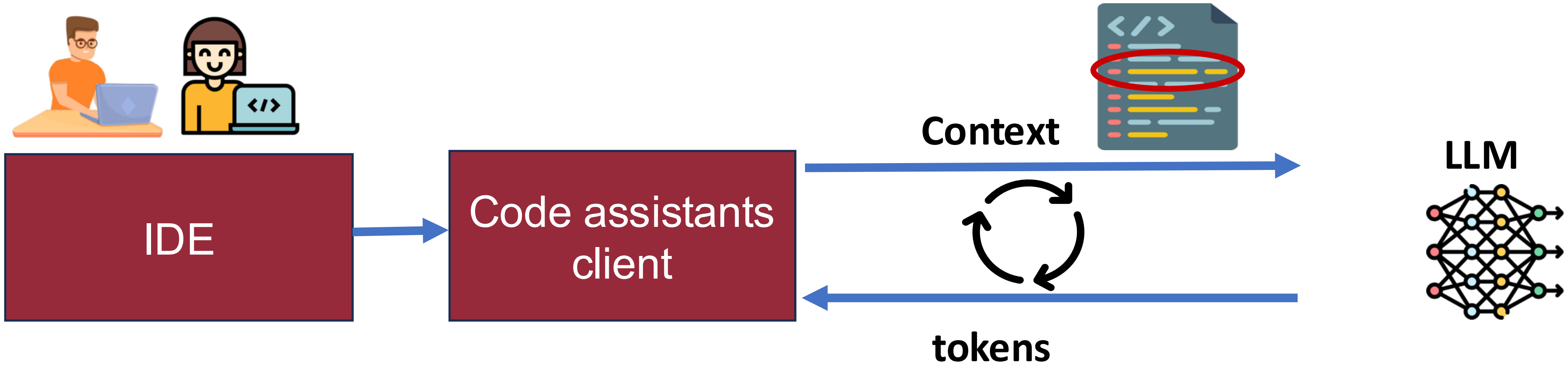
Slide: courtesy Shashi Ilager, University of Amsterdam

Resource-efficient inference in LLMs

- Knowledge Distillation
- Quantization
- Compression

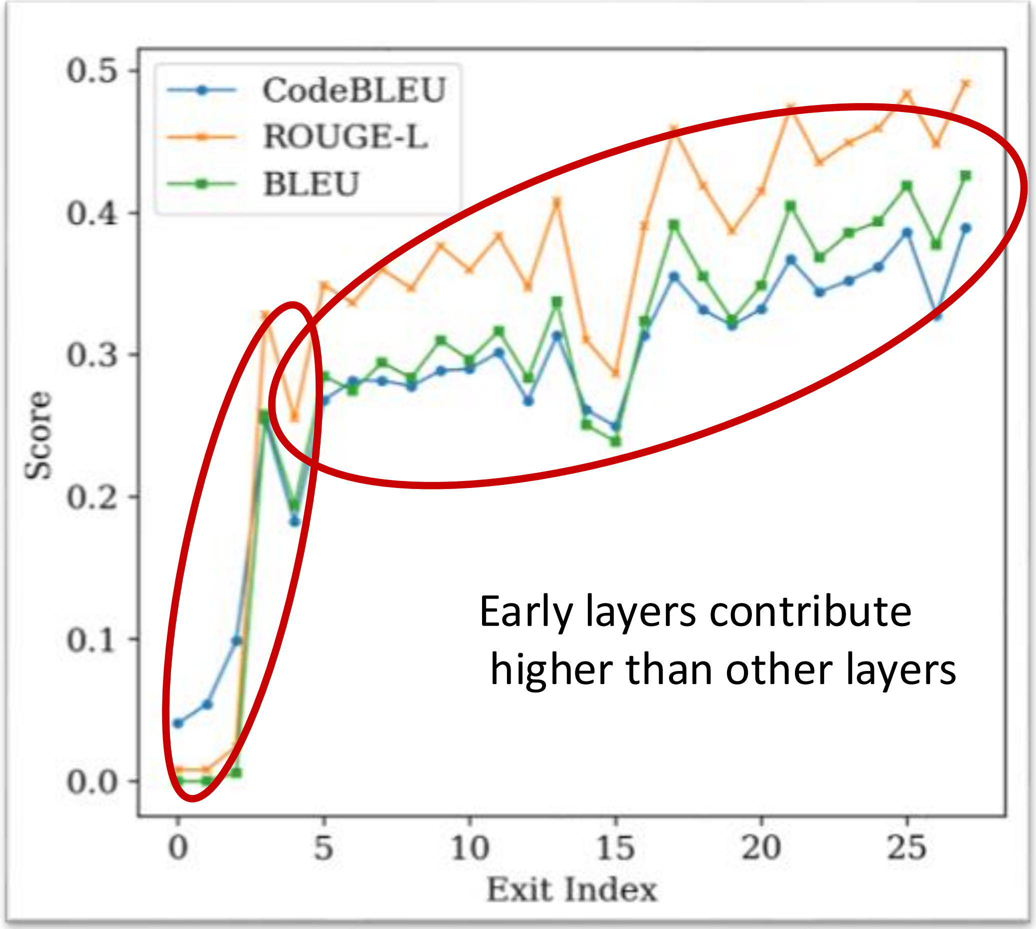
  - Introduces loss of accuracy
  - Non-adaptivity in runtime

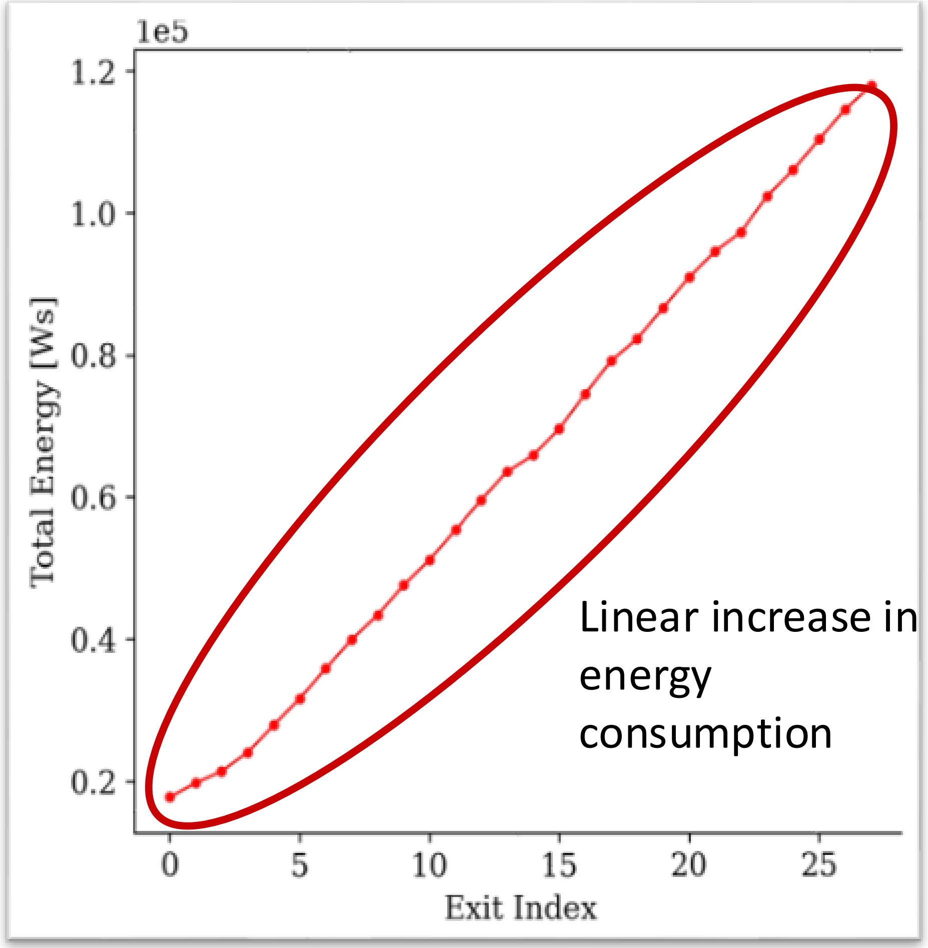
- Code generation is highly **dynamic**, with a different degree of complexity in each line of code
- Need to understand the **input context** (code file) and choose the corresponding inference load dynamically



Slide: courtesy Shashi Ilager, University of Amsterdam

Exploiting LLM's Linear Increase in Energy Consumption





Performance vs energy-consumption Llama3.2-3B/Java, fixed exits

Triton: Transprecise Edge Grant-DOI: 10.55776/P36870

Themis: Trustworthy and Sustaianble Code Offloading Grant-DOI: 10.55776/PAT1668223

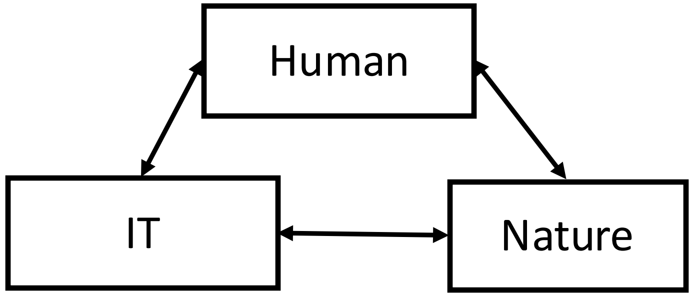
UNIVERSITY OF AMSTERDAM

Source: Shashikant Ilager, Lukas Florian Briem and Ivona Brandic. GREEN-CODE: Learning Energy Efficient Code Generation in LLMs, 2025 IEEE 25th International Symposium on Cluster, Cloud and Internet Computing (CCGrid), May 19-22 2025, Tromso, Norway.

Slide: courtesy Shashi Ilager, University of Amsterdam

Computational Sustainability

Actors:



chist-era

Sustainable Watershed Management Through IoT-Driven Artificial Intelligence

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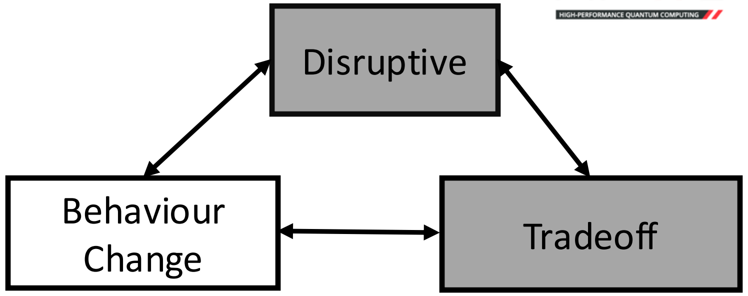
Methods:



HPQC

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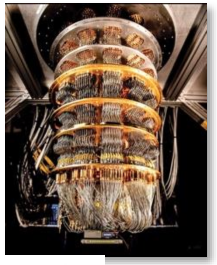
High Performance Integrated Quantum Computing



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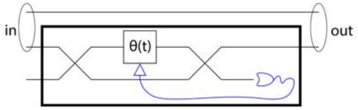
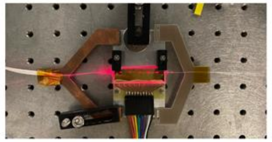
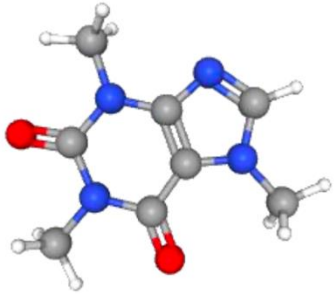




WWTF

WWTF: Advancing learning paradigms for photonic quantum processors

A cup of coffee?



"Every time you add a qubit, you double your possible outcomes, With 20 qubits there are a million possible outcomes. With 100 qubits, you have more possibilities than there are bits in all the hard drives in the world. With 300 qubits—that's more possibilities than there are particles in the universe."

- Representing the energy configuration of a single caffeine molecule at a single instant requires approximately 10^{48} bits in a classical computer

- Can be done using 160 logical qubits on a quantum machine

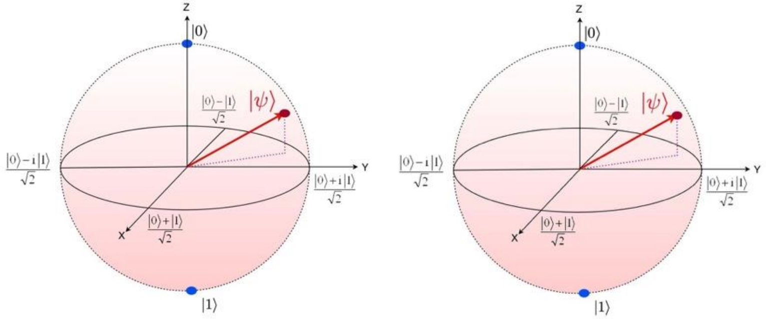
1 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 vs. 160

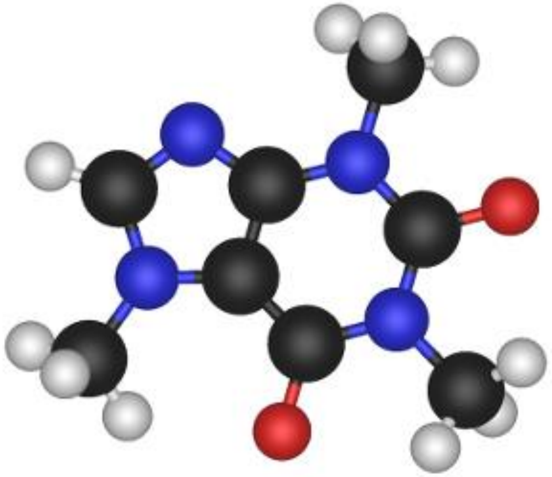
Courtesy Nico Einsiedler (IBM), TU Wien
Quantum Fall Fest 2022

https://quantum.duke.edu/2020/10/16/more-possibilities-than-there-are-particles-in-the-universe/

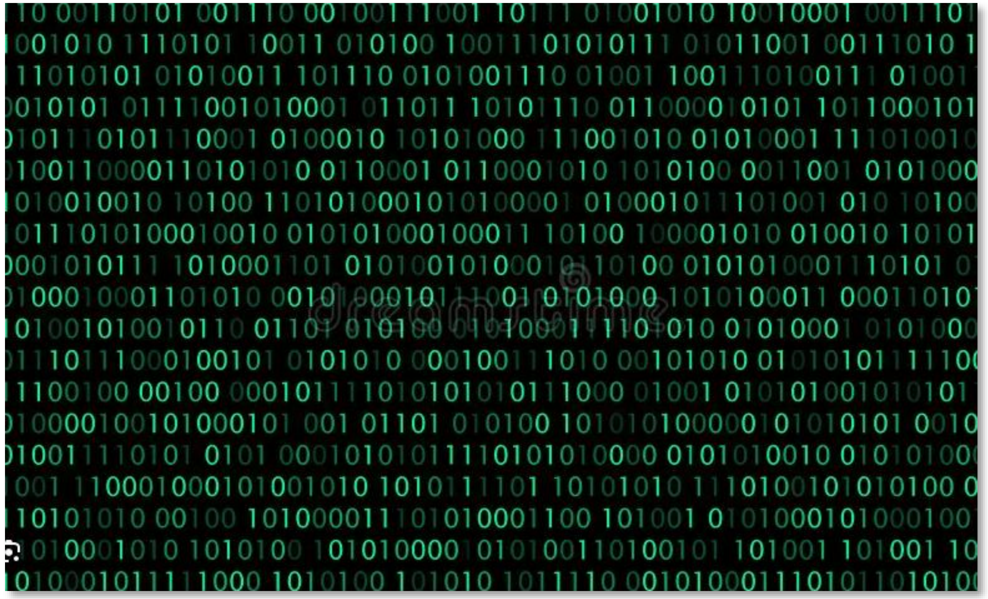
Beyond 0 and 1

Quantum





Von Neumann



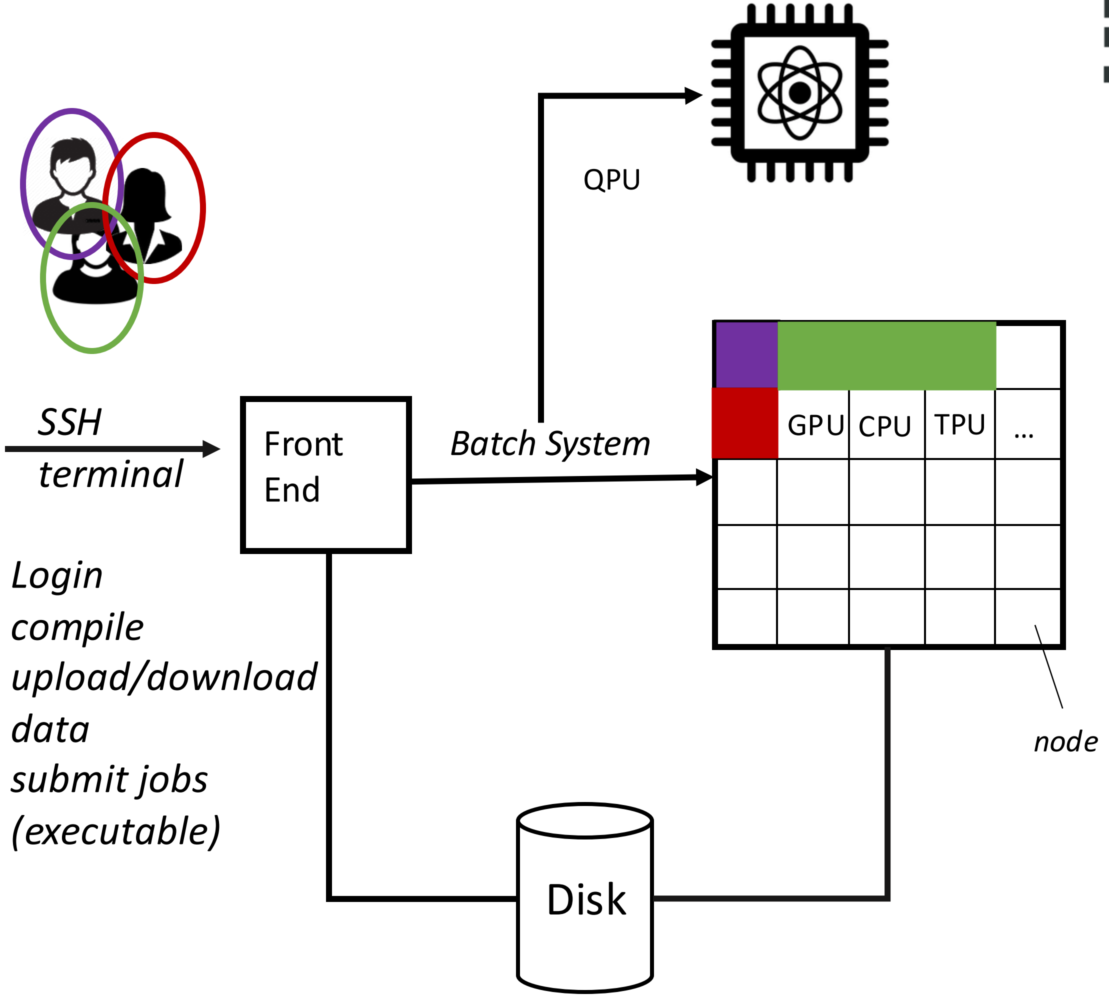
Bottom up approach

- *Variational Quantum Linear Solver (VQLS)*
- *Quantum Eigenvalues* –> **Native 3d modeling of scientific applications**

Problem: Currently quantum systems can be used by quantum researchers only!

HPC Cluster

- Each “node” has its own operating system
- Nodes are interconnected with a network cable
- Higher performance demand more processors
- Accessed via front-end node/computer
- Shared with may users



- *Login*
- *compile*
- *upload/download data*
- *submit jobs (executable)*

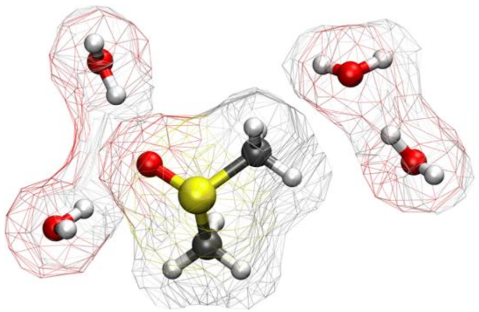
FFG High Performance Integrated Quantum Computing
Grant ID: #4562957

HPQC
HIGH-PERFORMANCE QUANTUM COMPUTING

HPQC Cluster

- Improve QC performance
- Complement QEC capabilities
- Extend QC research with HPC

- Implement Hybrid Q-Libs
- **Benchmark PoC use-cases in hybrid infrastructure (HPC TU Wien)**



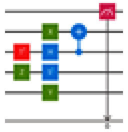
QML

Direct access

Login console

HPC node

aconet



Circuit API

Offloading API

QC system

S. Herbst

V. De Maio

M. Kanatbekova

F. Zilk

→ Best Paper Award at ISVLSI 2025
→ FGCS2024 Fall Editor's Choice Award
→ Dieberger-Skalicky Prize 2025
→ NetIdee Scholarship 2024
→ DISCOVER US Scholarship 2026

AQT · JKU JOHANNES KEPLER UNIVERSITÄT LINZ · universität innsbruck · IBM · MATH+TEC · TU WIEN · FFG Forschung wirkt.

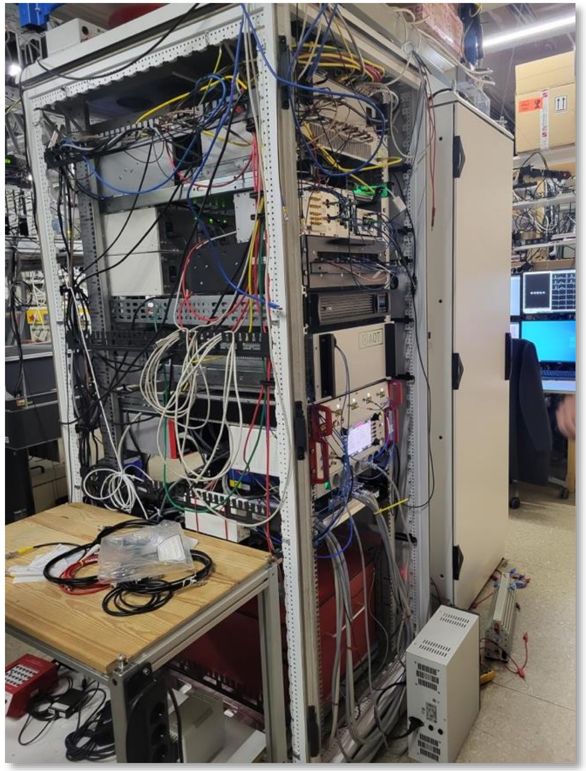
Assembly of a Quantum Processing Unit (QPU)

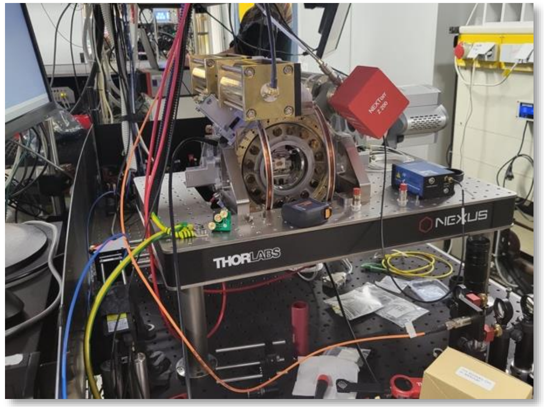
Picture: Courtesy AQT; Uni Innsbruck

- Move from Ca+ to Ba+
- New system with
  stage 1: 10x higher T_1
  stage 2: infinit. Higher T_1
- 2q error rate:
  legacy: $< 10^{-2}$
  target: $< 10^{-3}$
- Init error
  legacy: $< 10^{-3}$
  target: $< 10^{-4}$
- Readout error
  legacy: $< 10^{-3}$ -> ~ 10^{-4}
  target: $< 10^{-5}$

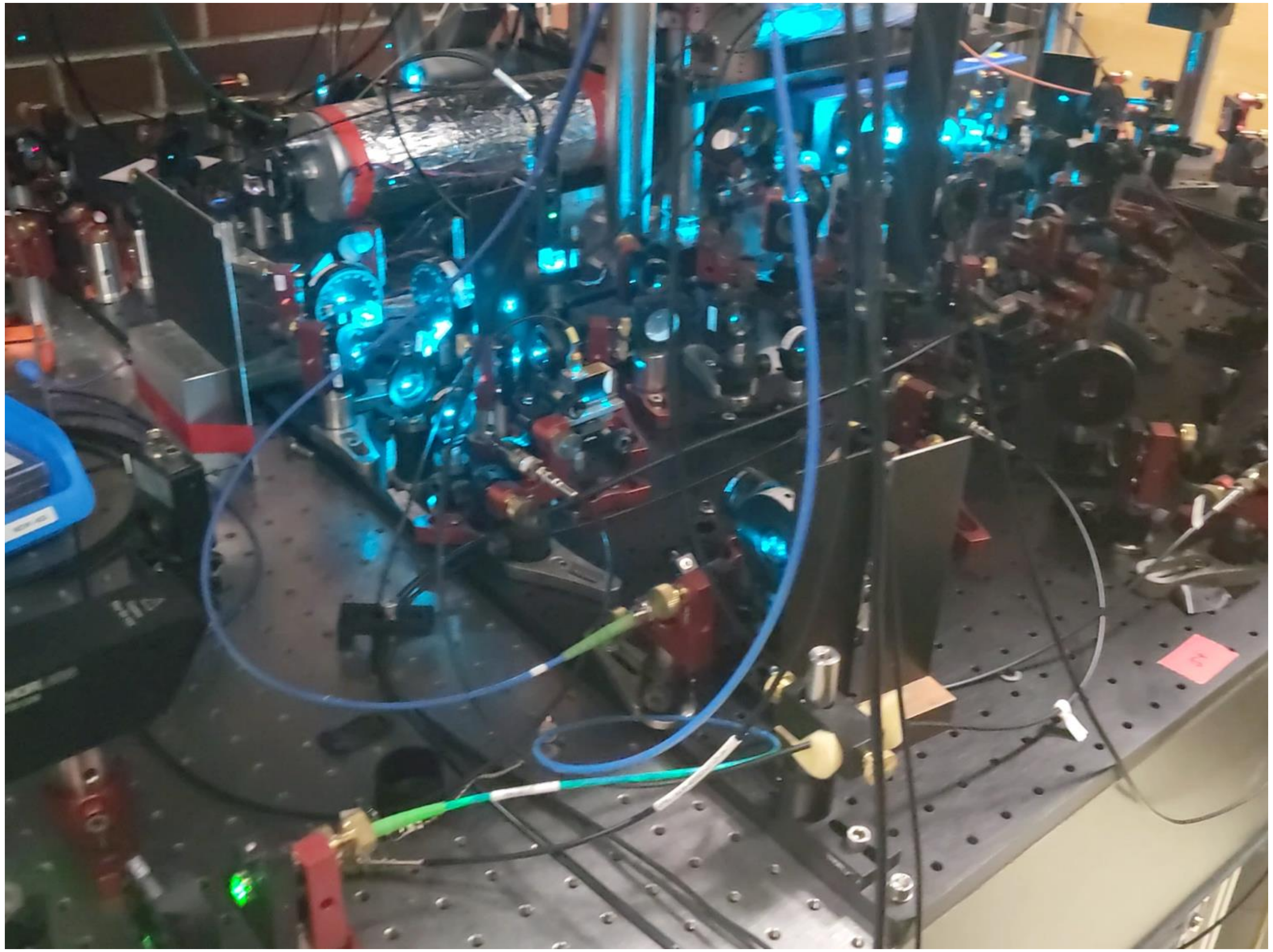
universität innsbruck

HPQC HIGH-PERFORMANCE QUANTUM COMPUTING



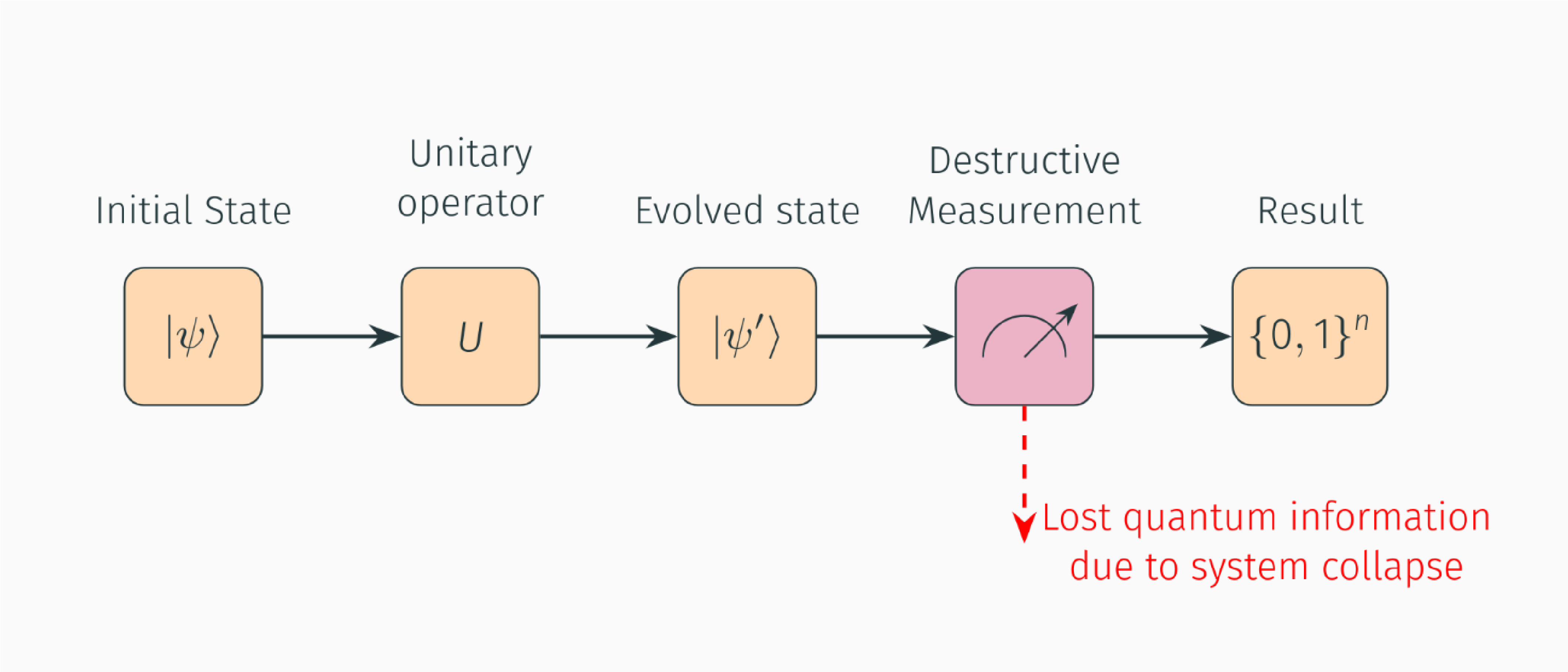


Ion-trap quantum computer

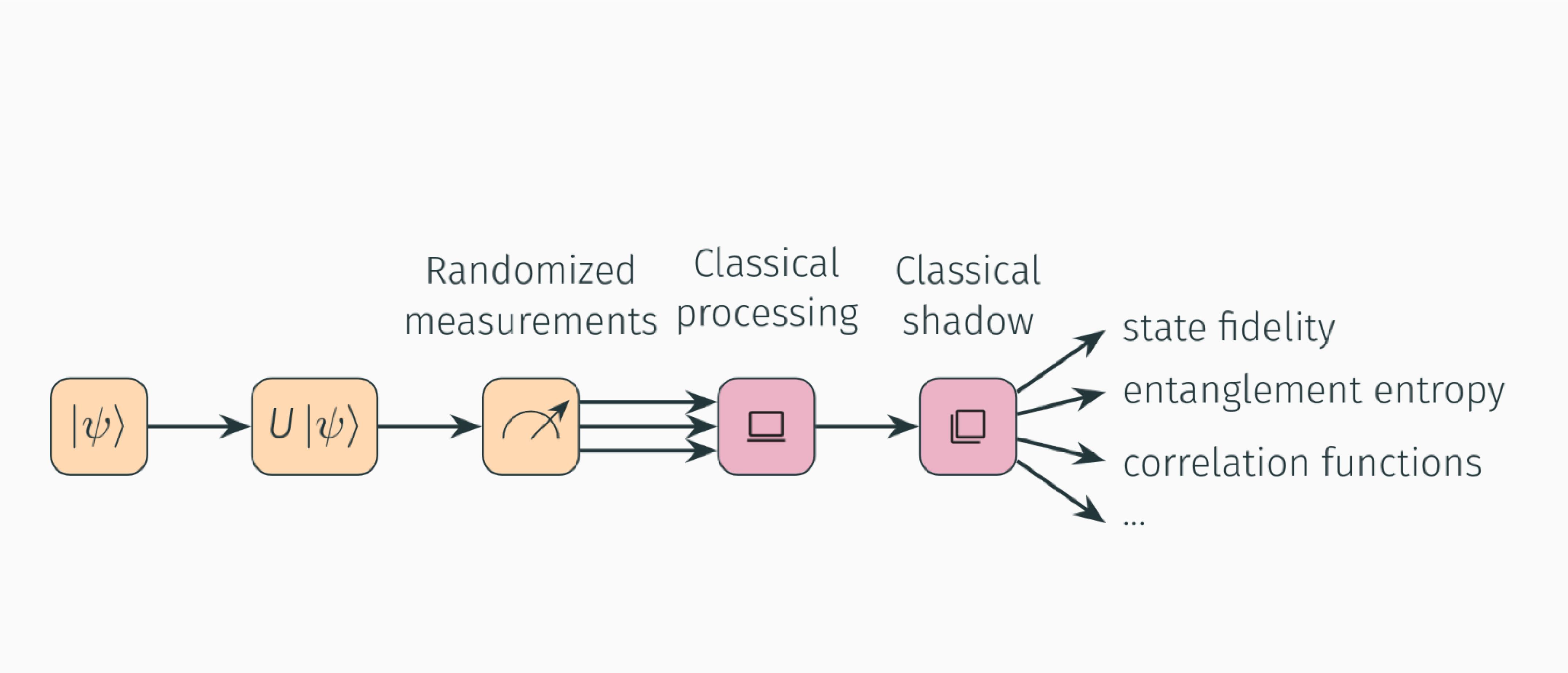


Courtesy Experimentalphysik, Univ. Innsbruck
Pictures, video: courtesy Vincenzo de Maio

Destructive Measurements



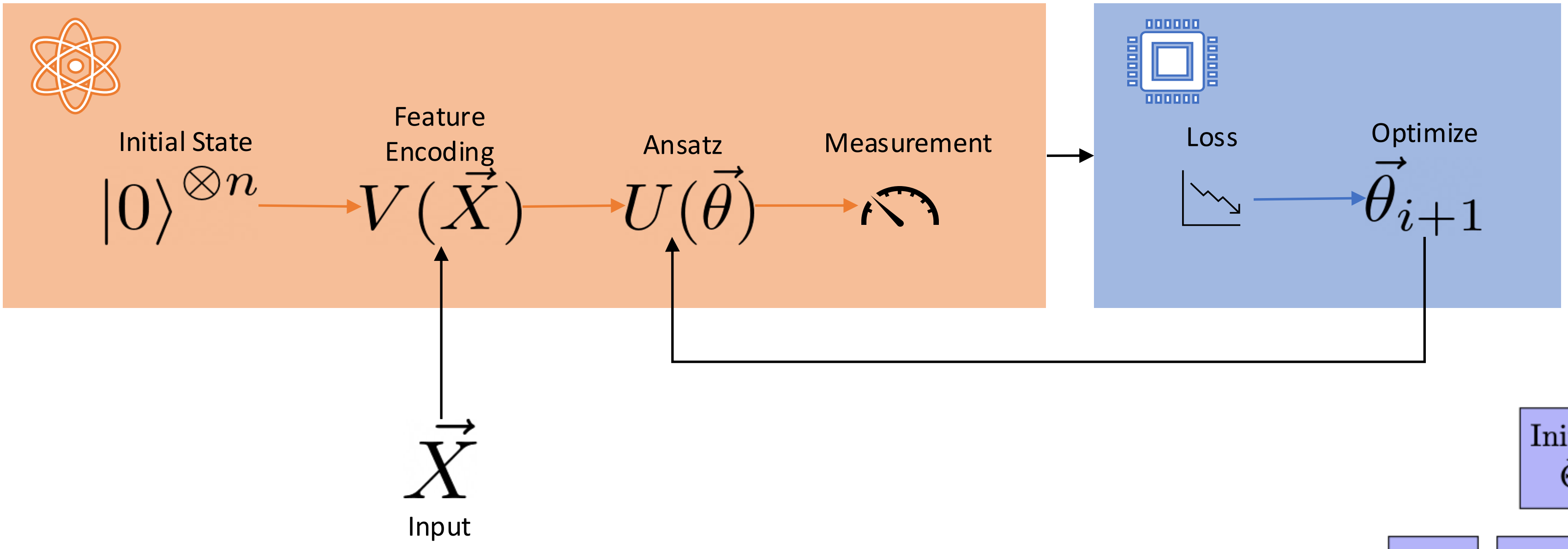
Classical Shadows

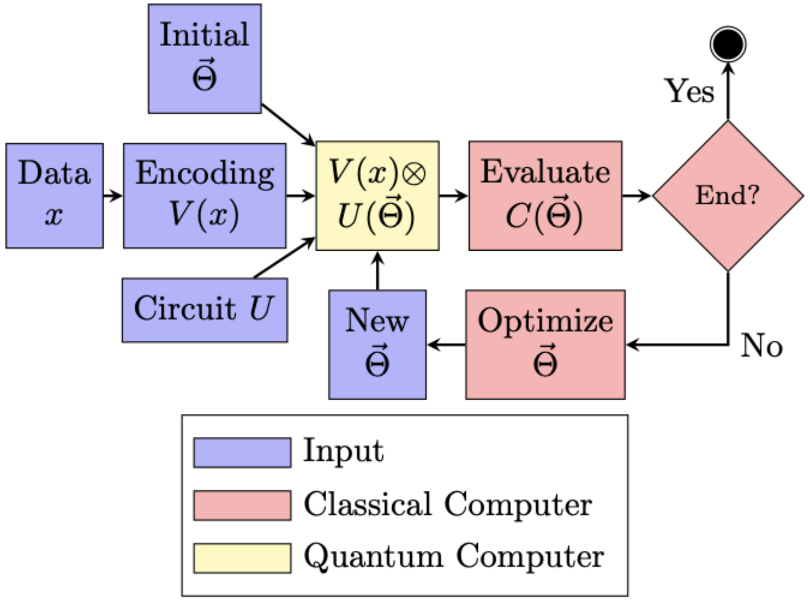


Source: Huang, HY., Kueng, R. & Preskill, J. Predicting many properties of a quantum system from very few measurements. Nat. Phys. 16, 1050–1057 (2020).

Slide courtesy: S. Herbst

Quantum Neural Network (QNN)

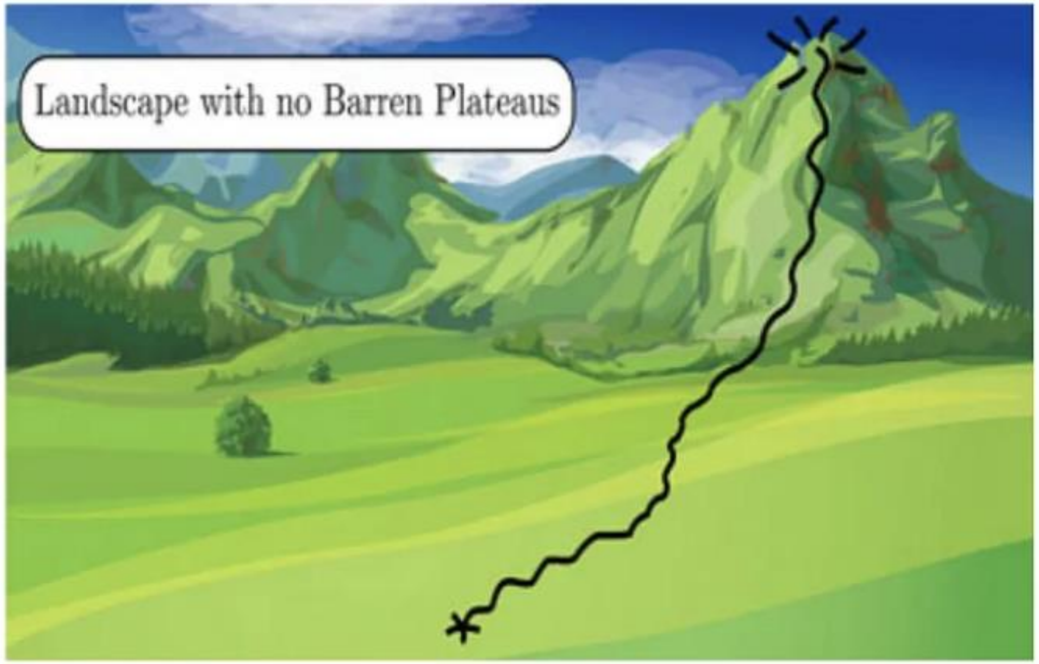


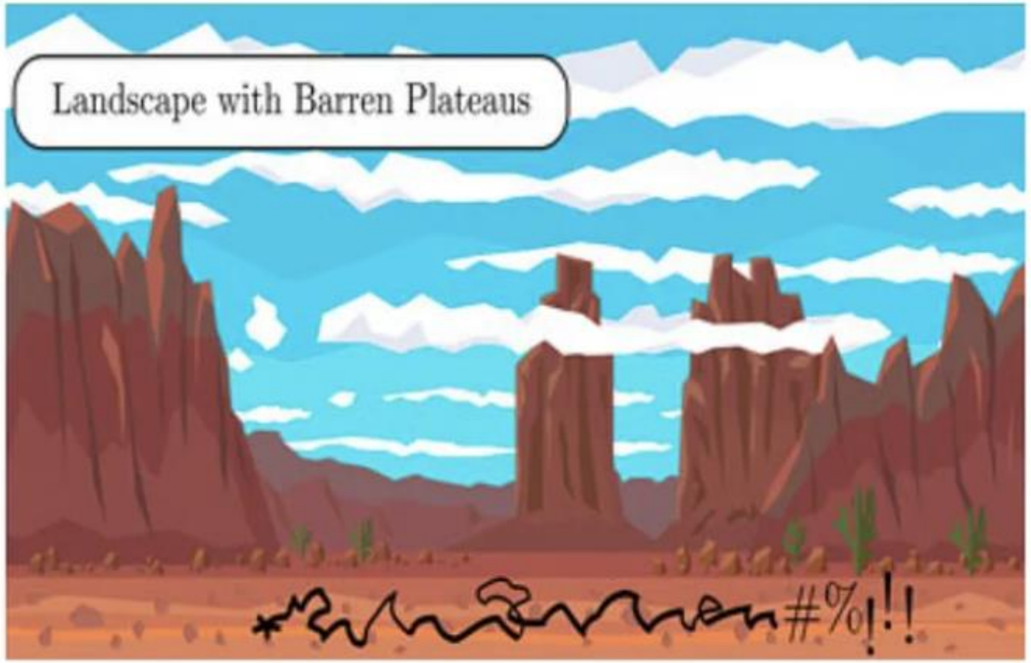


Source: Sabrina Herbst, Vincenzo De Maio, Ivona Brandic: On Optimizing Hyperparameters for Quantum Neural Networks. QCE 2024: 1478-1489

Slide courtesy: S. Herbst

Barren Plateau





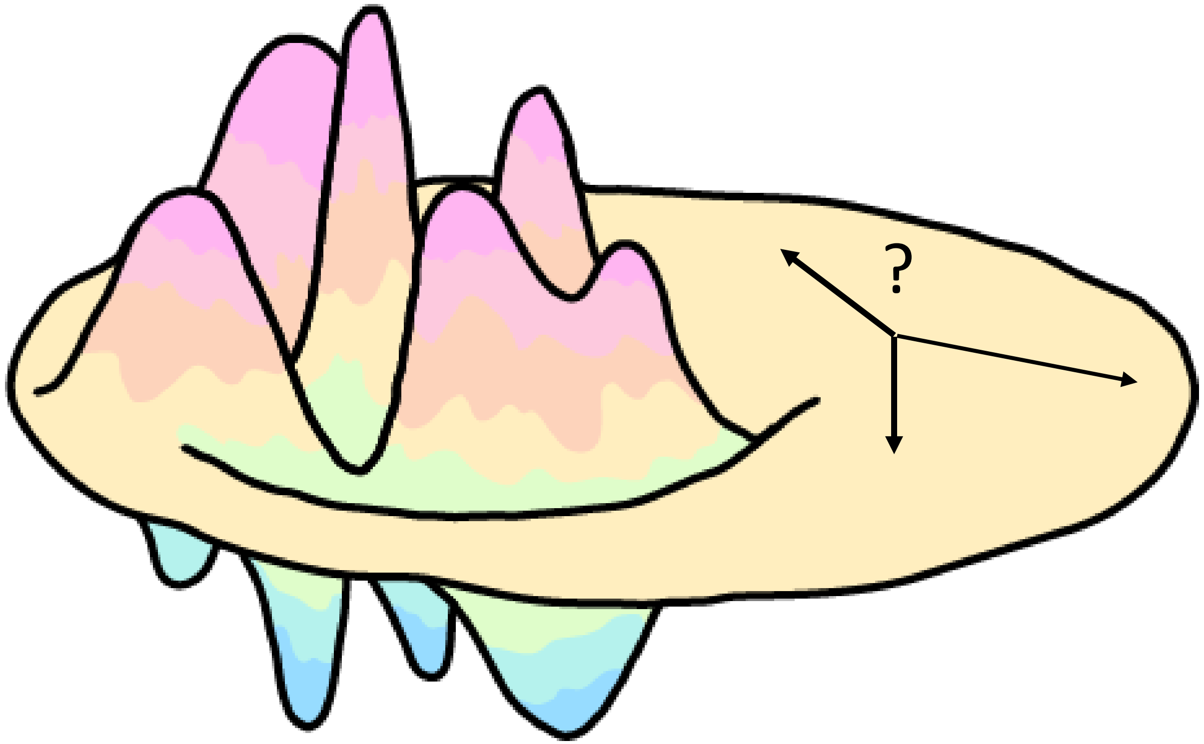
Source: https://medium.com/@deltorobarba/can-quantum-computing-accelerate-generative-ai-b1df36398ac5

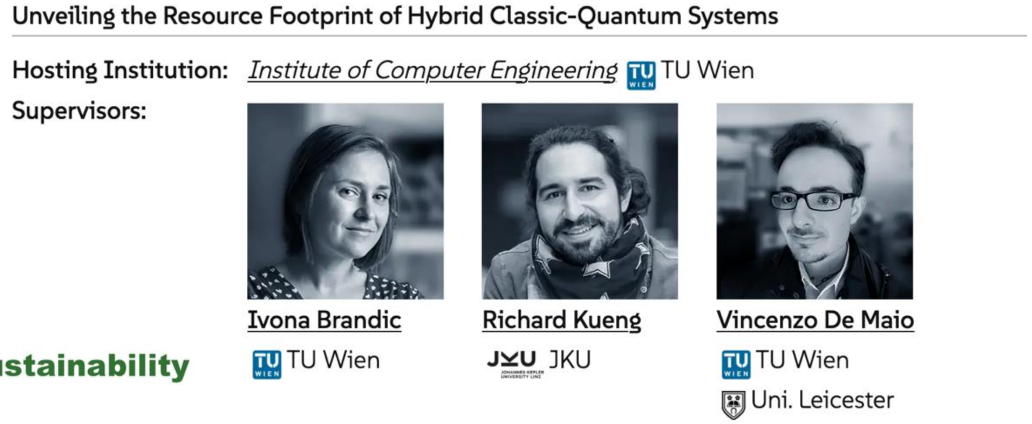
optimization landscape

- gradient of the cost function with respect to the circuit parameters becomes **exponentially small** as the system size increases.
- **training the model extremely difficult**, as gradient-based optimization essentially stalls—similar to being stuck on a flat, featureless desert with no clear direction to go.

Implications for QML

- **Training fails**: Gradient descent becomes ineffective, especially as the number of qubits increases.
- **Wasted resources**: Running quantum circuits that don’t contribute to learning wastes both time and quantum compute resources.
- **Scalability issues**: Makes it hard to train larger QML models.

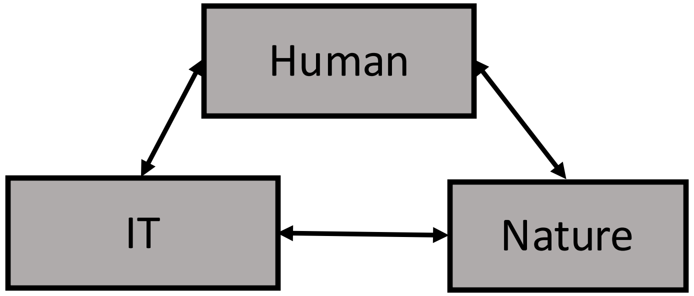




Doctoral College Computational Sustainability

Computational Sustainability

Actors:



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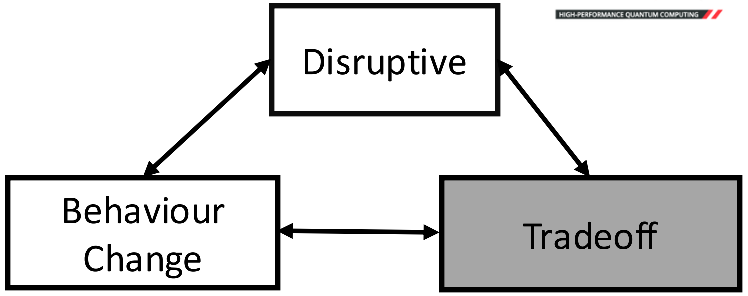
Sustainable Watershed Management Through IoT-Driven Artificial Intelligence

FFG Forschung wirkt.

Virtual Shepherd

TRUST! Explaining the increasing energy consumption of IT infrastructures

Methods:



Doctoral College Computational Sustainability

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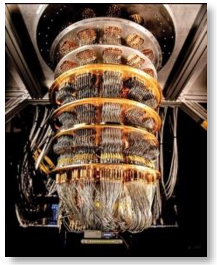
HPQC HIGH-PERFORMANCE QUANTUM COMPUTING

FFG Forschung wirkt.

High Performance Integrated Quantum Computing



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Quantum Algorithm Enginering COMET Module

W|W|T|F

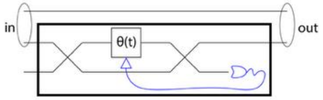
WWTF: AI-supported Holographic Environmental Water Monitoring

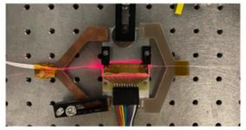
FWF

Themis: Trustworthy and Sustaianble Code Offloading

FWF

Triton: Transprecise Edge





W|W|T|F

WWTF: Advancing learning paradigms for photonic quantum processors

Siberia's gateway to the underworld

Source: https://www.science.org/content/article/siberia-s-gateway-underworld-grows-record-heat-wave-thaws-permafrost

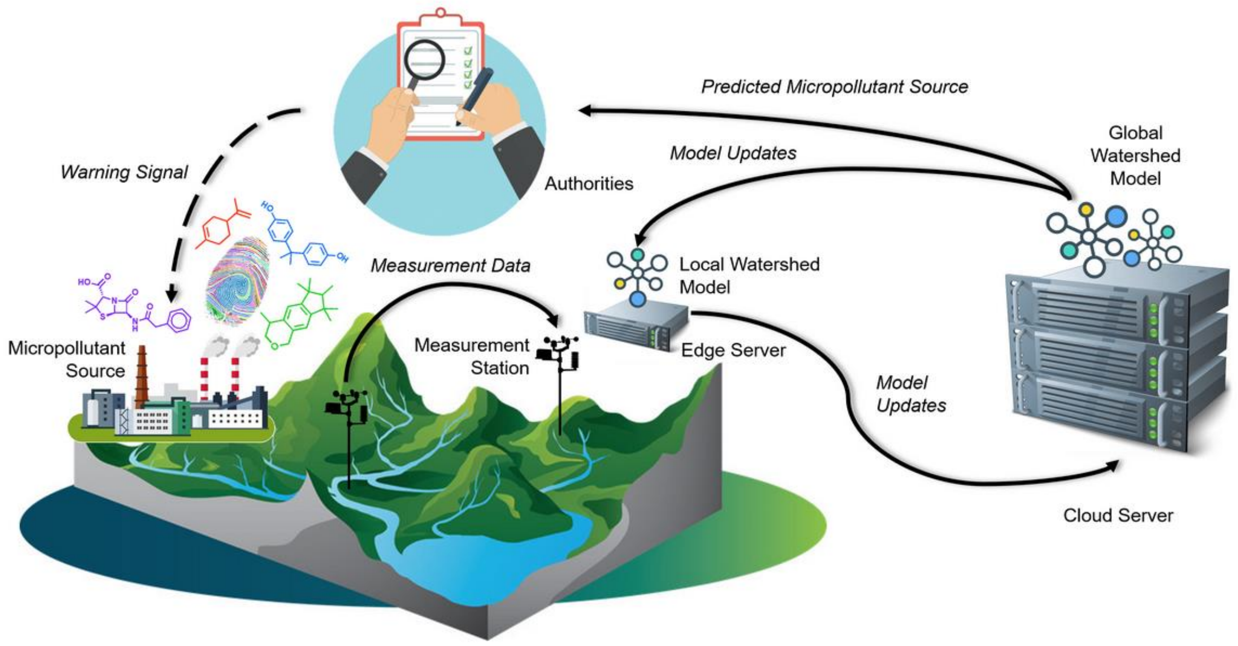
Batagaika crater

Ambarnaya river, Norilsk, Siberia
Source: https://www.brusselstimes.com/news/115566/u-s-offers-to-help-russia-following-arctic-oil-spill/

SWAIN - Sustainable Watershed Management Through IoT-Driven Artificial Intelligence

chist-era FWF
CHIST-ERA-19-CES-005

- In-silico digital representation of the river
- viscoelasticity
- **Data from IoT sources + expert knowledge = digital model of the river**

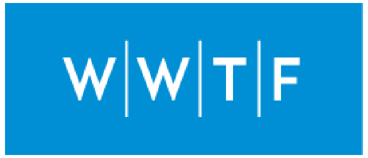


TU WIEN
BOĞAZİÇİ ÜNİVERSİTESİ 1863
universität wien
SYKE
Finnish Environment Institute

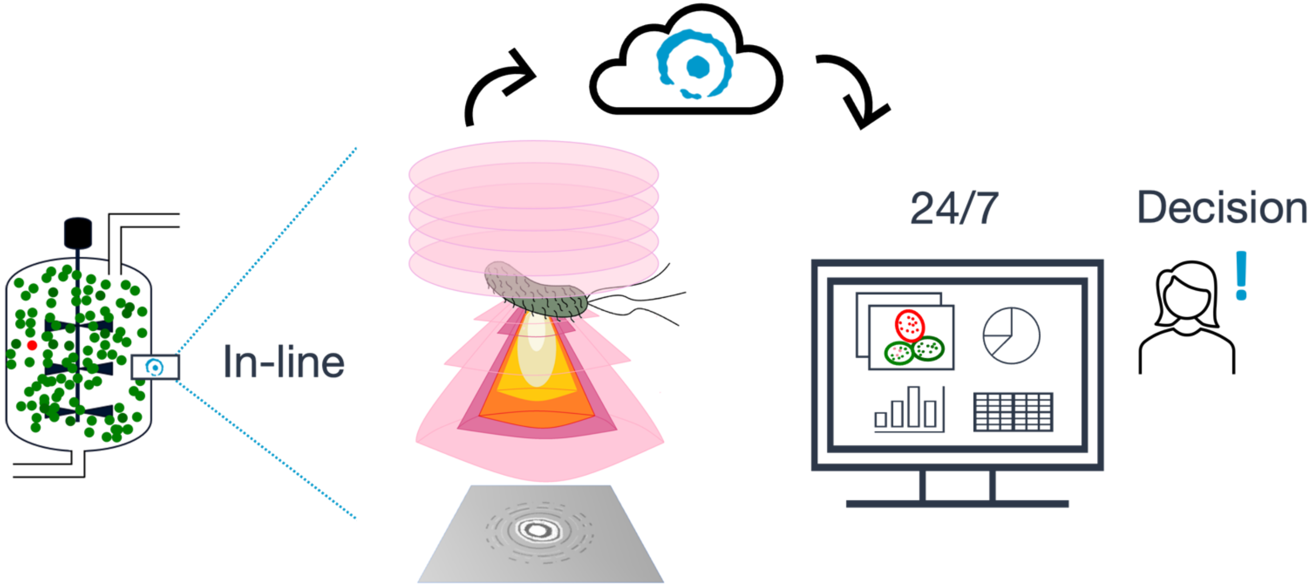
Source: S. Ahmad, H. Uyanık, T. Ovatman, M. T. Sandıkkaya, V. De Maio, I. Brandic, A. Aral. Sustainable Environmental Monitoring via Energy and Information Efficient Multi-Node Placement. IEEE Internet of Things Journal


Wasserversorgung der Stadt Wien
Donau
Wasserwerk Nußdorf
WIEN
Wasserwerk Lobau
St. Pölten
II. Wiener Hochquellenleitung
Mödling
III. Wiener Wasserleitung
Wasserwerk Moosbrunn
Scheibbs
Umgehungsstollen Scheibbs
Baden
NIEDERÖSTERREICH
Wagstollen
I. Wiener Hochquellenleitung
Lunz
Wr. Neustadt
Mariazell
Fuchspassquelle u. a.
Stixenstein-
quellen
Behälter Neusiedl
Wasseralmquelle
Brunngrabenquellen
Gußwerk
Kaiser-
brunnen
Holzäpfeltal-
quelle
Pfannbauernquelle
Höllental-
qu.
Neunkirchen
Pirknerquelle
Schneealpenstollen
Wildalpen
Hirschwang
Höllbachquellen
Sieben Quellen
Seisensteinquelle
Kläfferquellen
Mürzzuschlag
Schreier-
klammquellen
Siebensee-
quellen
STEIERMARK
LEGENDE
Quelle
Brunnen
Wasserbehälter
Wasserleitungen
Schutz- und Schongebiet
Grafik-Wiener Wasserwerke

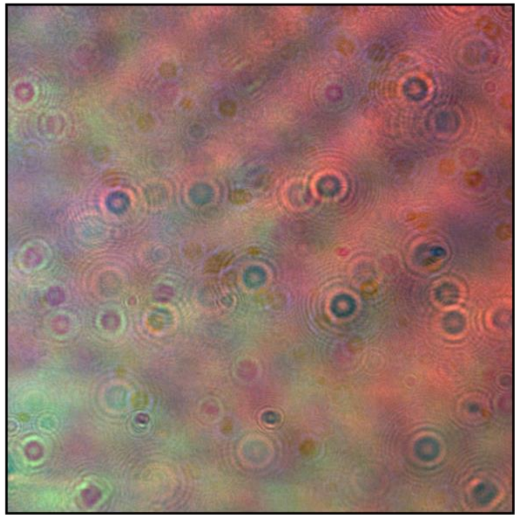
Holographic microscopy



 # ESR24-053
AI-supported Holographic Environmental Water Monitoring



- Our device has the size of a shoebox
- It collects liquids and shines light through them
- Some light is scattered by any particles inside
- The illuminating and scattered light interfere forming holograms that are recorded by a camera
- The preprocessed images and sent to the cloud
- The light in the volume is numerically reconstructed to ~500 images in a stack
- The total volume of view is ~1M times that of a conventional microscope
- Proprietary algorithms boost the contrast and resolution
- The whole platform provides real time microscopic monitoring



Slide: courtesy Peter van Oostrum, Holloid, BOKU Wien

Holloid
Big data on small things

Thanks to funding agencies and my team

European Commission | Horizon 2020 European Union funding for Research & Innovation

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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W|W|T|F

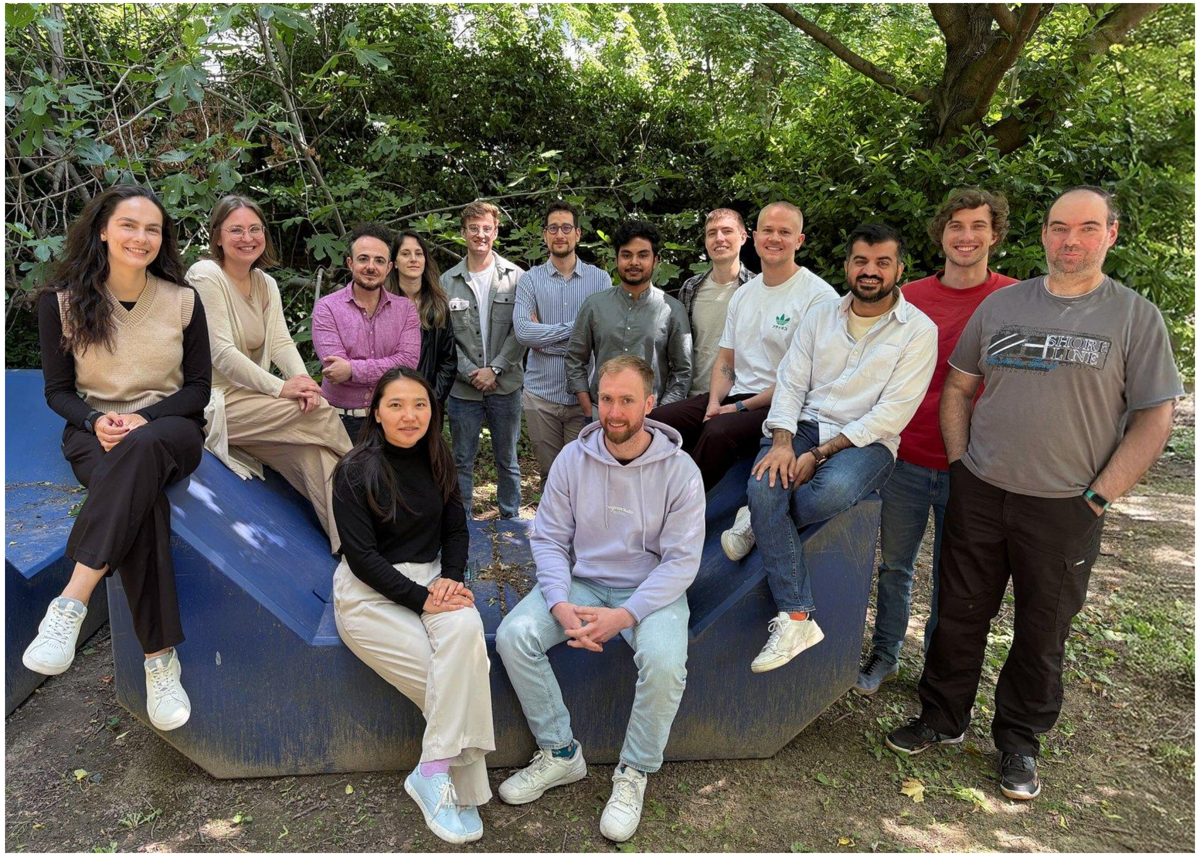
QUANTUM AUSTRIA

Stadt Wien

MARIE CURIE ACTIONS

FWF

FFG Forschung wirkt.



SFG

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Bundesministerium Frauen, Wissenschaft und Forschung