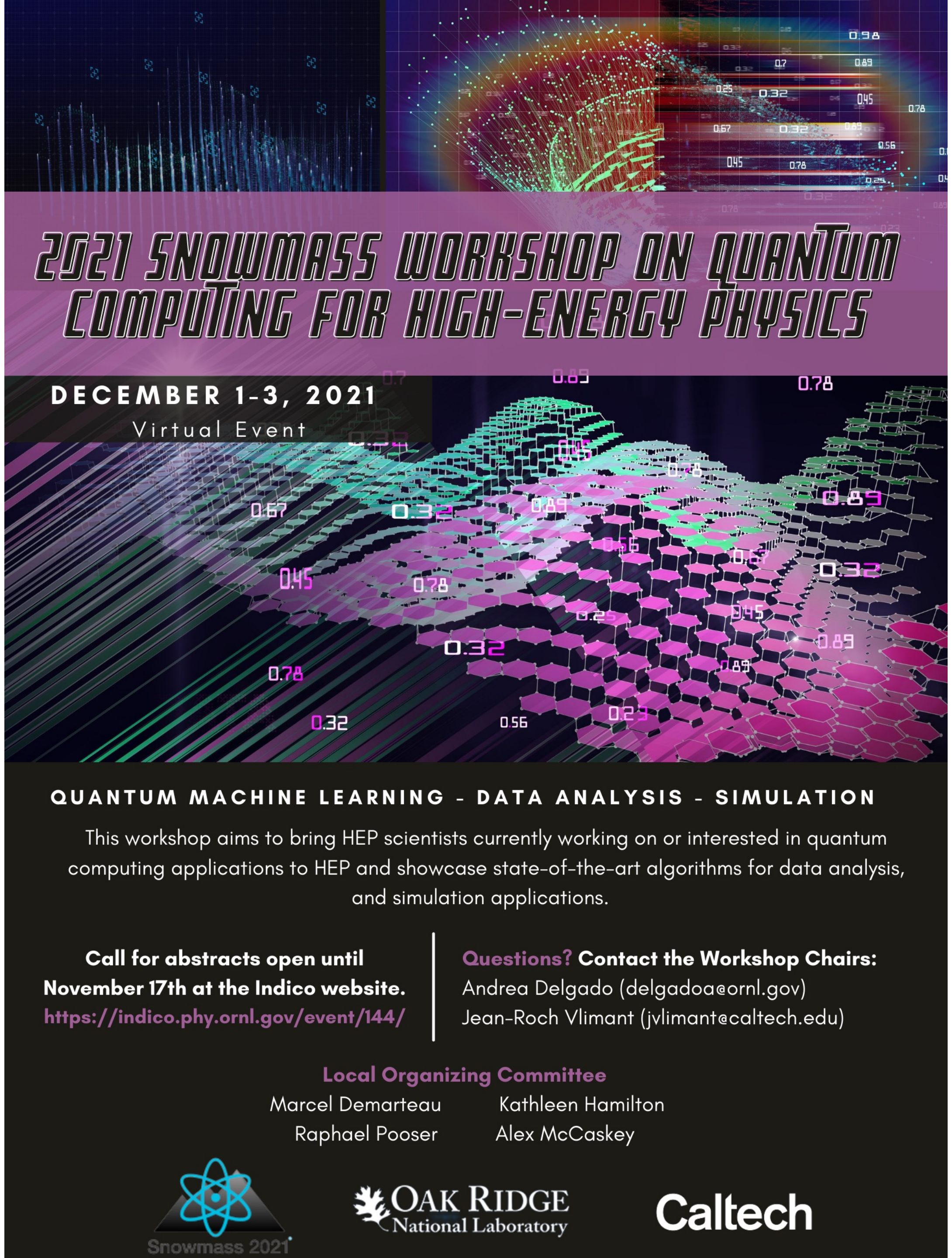
Quantum Computing for Data Analysis in High-Energy Physics

Andrea Delgado (she/her/ella)
On behalf of the whitepaper team

arXiv:2203.08805

Visit Workshop Website!

Recordings of talks available



Quantum Computing for High-Energy Physics

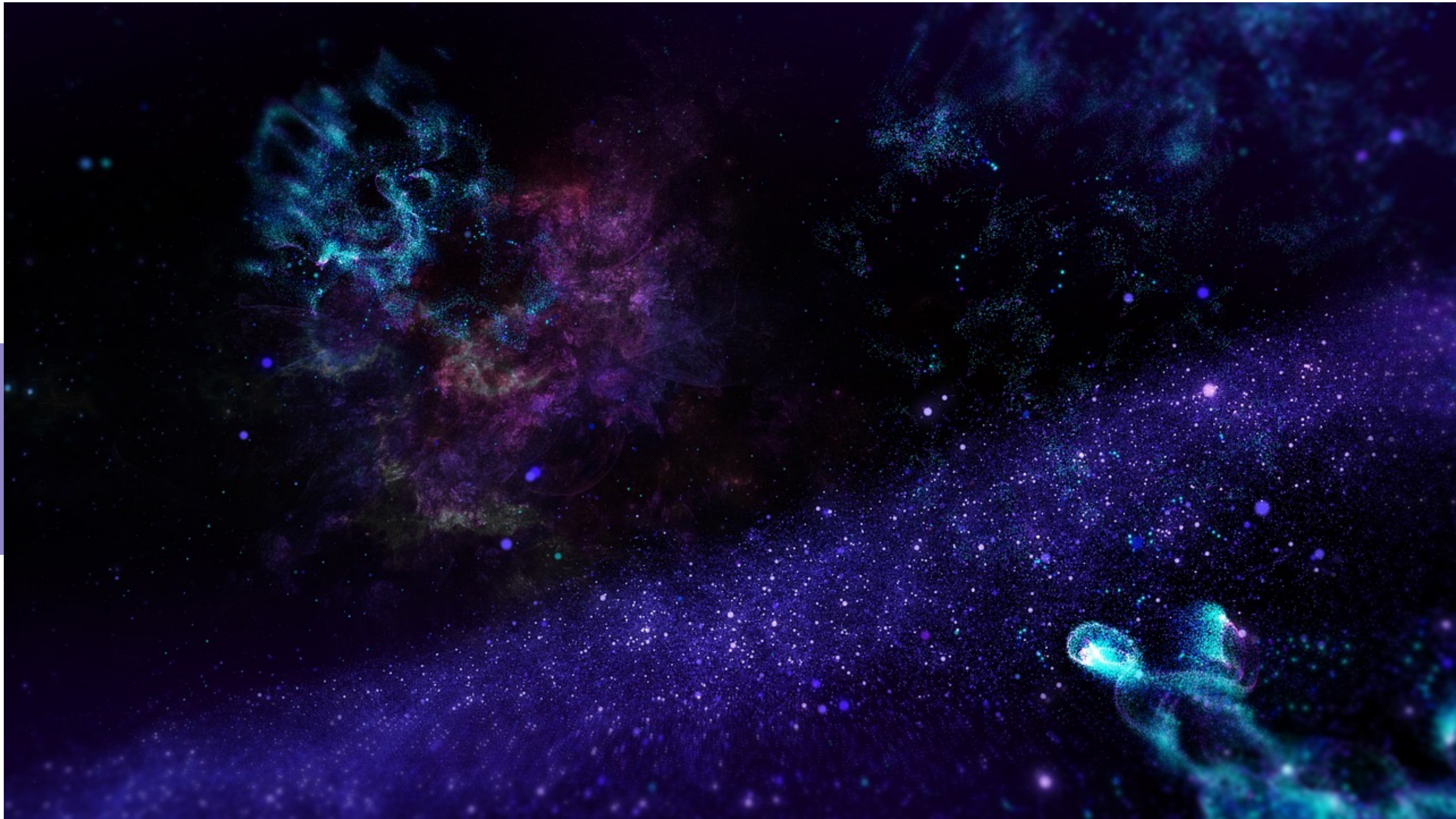
Hilbert space is a big place!

Carlton Caves

With 275 qubits, we can represent more basis/computational states than the number of atoms in the observable universe.

2^{275}

The potential to speed up certain calculations, simulate quantum mechanical systems through the manipulation of quantum mechanical properties such as entanglement.



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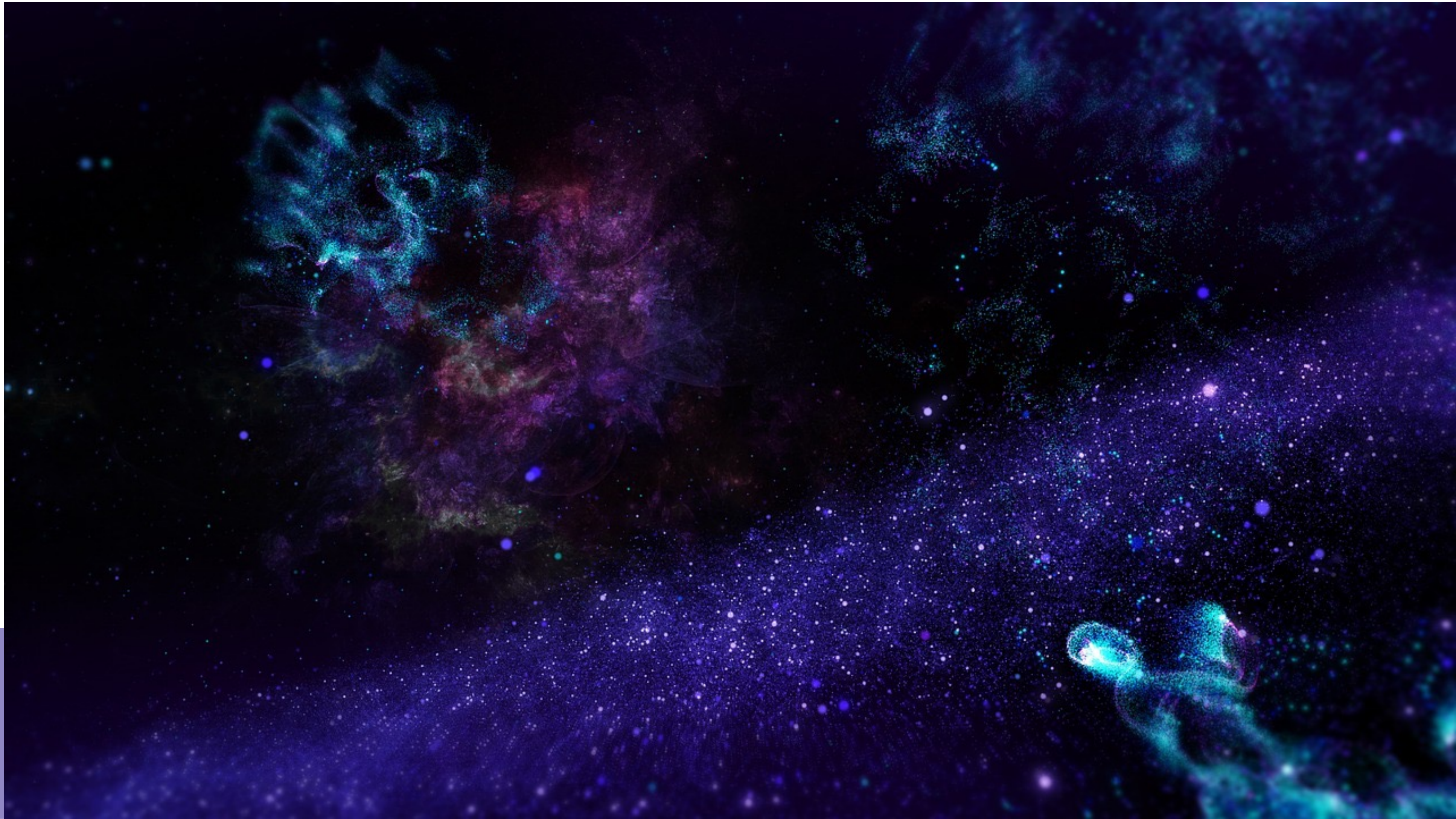
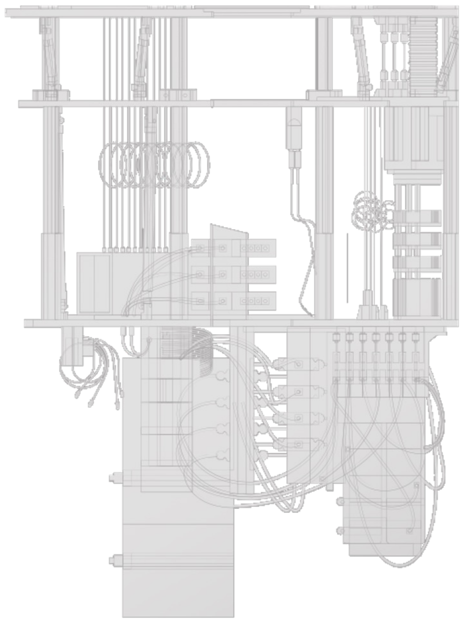
Not as easy as it sounds!

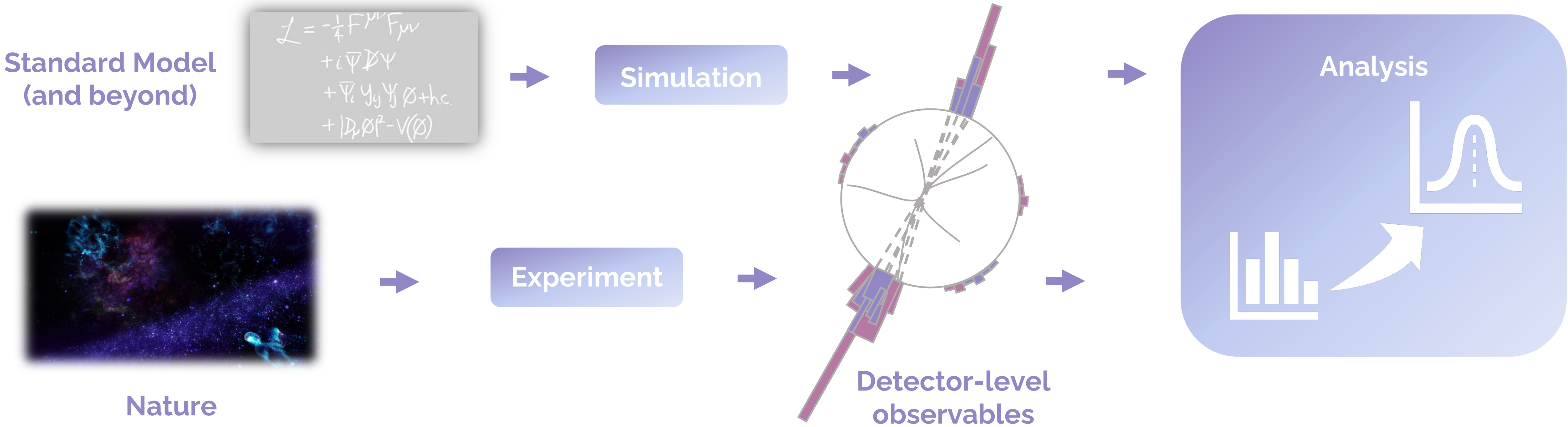


Quantum Computing in the NISQ Era

★ Motivated by access to **cloud-based** processors and commercial applications.
★ Applications in **Quantum Machine Learning (QML)** spurred by the release of Xanadu's PennyLane / Google's Tensorflow.
★ **Co-design**:
  - *Algorithmic development/research is adapting to match the pace of hardware development.*
★ Applications in quantum annealing, superconducting qubits, and continuous-variable explored.
★ Developed for deployment on **NISQ** devices.
  - Few qubits,
  - Noisy,
  - Low gate fidelity.
★ Hybrid frameworks to leverage benefits of both classical and quantum computing - ***variational quantum circuits***.

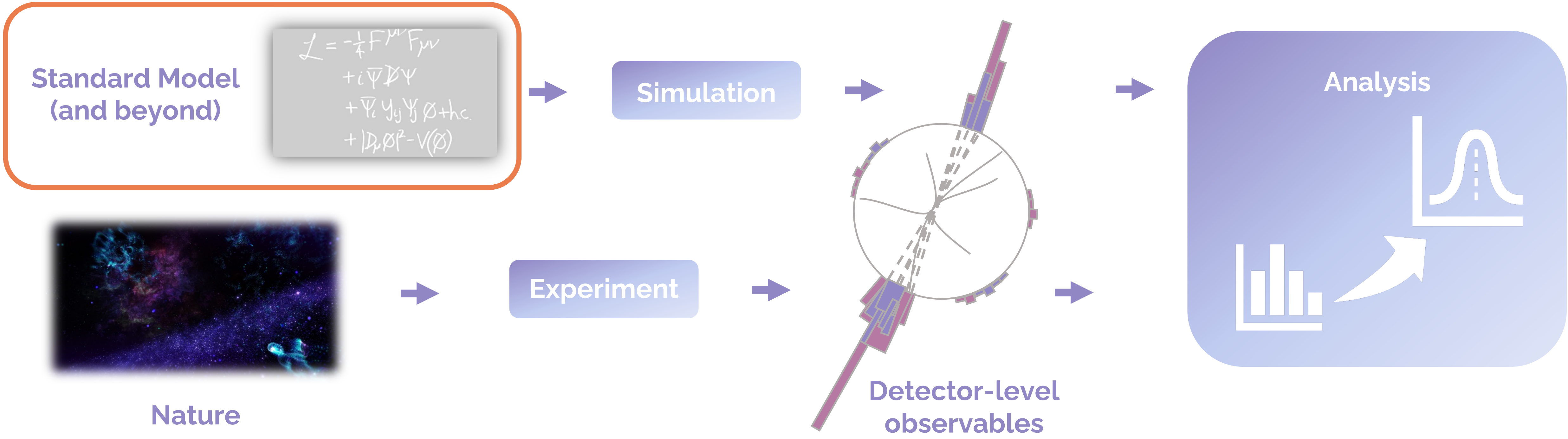


Data Analysis in High-Energy Physics



Data Analysis in High-Energy Physics

See Christian Bauer's talk on "Quantum Simulation"



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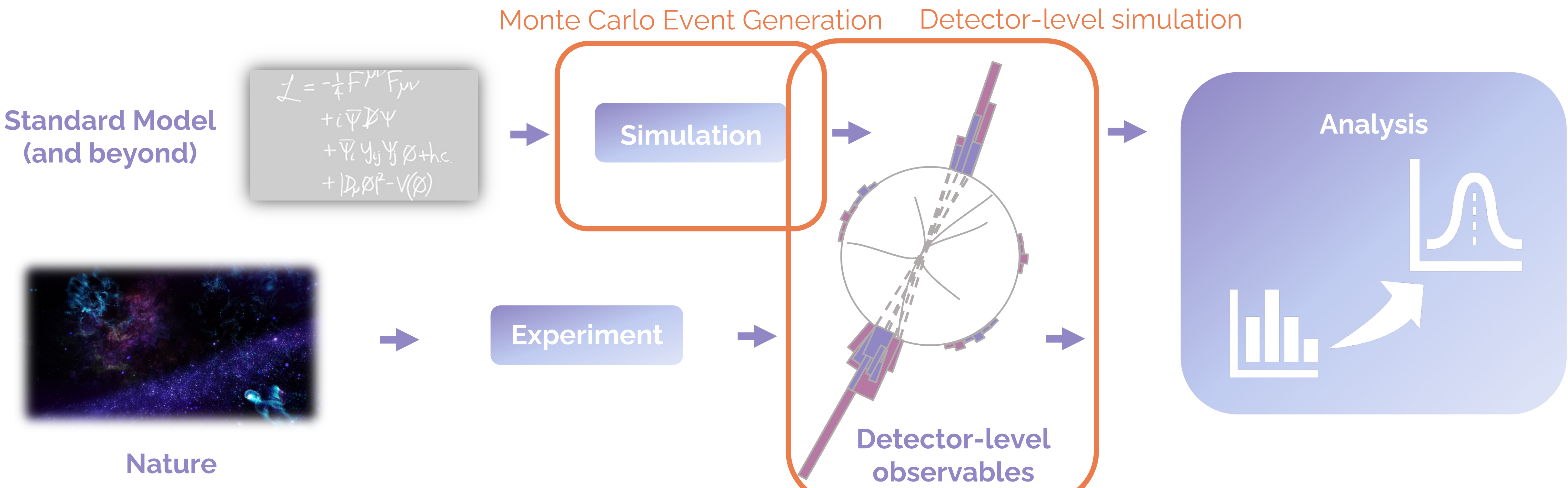


Quantum-enhanced generative modeling

- GANS and QCBMs.
- Studied in the context of data augmentation.
- Challenges associated with the encoding of target distributions and scalable quantum error correction techniques.
- Important for building up the "quantum pipeline" – in anomaly detection settings, intermediary encoders, etc.

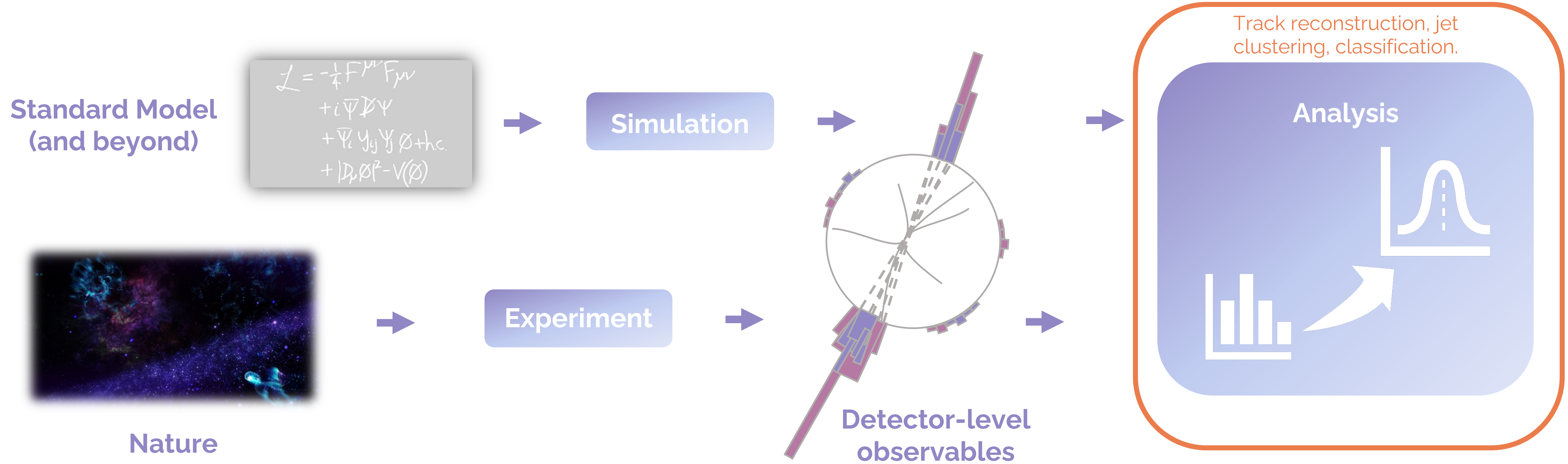
"Style-based quantum generative adversarial networks for Monte Carlo events", Bravo-Prieto, Baglio, Cè, Francis, Grabowska, Carrazza, **arXiv:2110.06933**

"Quantum integration of elementary particle processes", Agliardi, Grossi, Pellen, Prati, **DOI:10.1016/j.physletb.2022.137228**

"Unsupervised Quantum Circuit Learning in High-Energy Physics", Delgado, Hamilton **arXiv:2203.03578**

"Conditional Born machine for Monte Carlo events generation", Kiss, Grossi, Kajomovitz, Vallecorsa **arXiv:2205.07674**

Data Analysis in High-Energy Physics



Casting Data Analysis Tasks as Optimization Problems

- Reformulating clustering tasks as binary unconstrained satisfaction problems (QUBO).
- Motivated by access to D-Wave QPUs.
- Large number of available qubits, relatively easy to program.

Zlokapa, A., Anand, A., Vlimant, J.R. *et al.* **Charged particle tracking with quantum annealing optimization**. *Quantum Mach. Intell.* **3**, 27 (2021).

Quiroz, G., Ice, L., Delgado, A., Humble, T.S., **Particle track classification using quantum associative memory**, Nuclear Instruments and Methods in Physics Research Section A, Volume 1010 (2021).

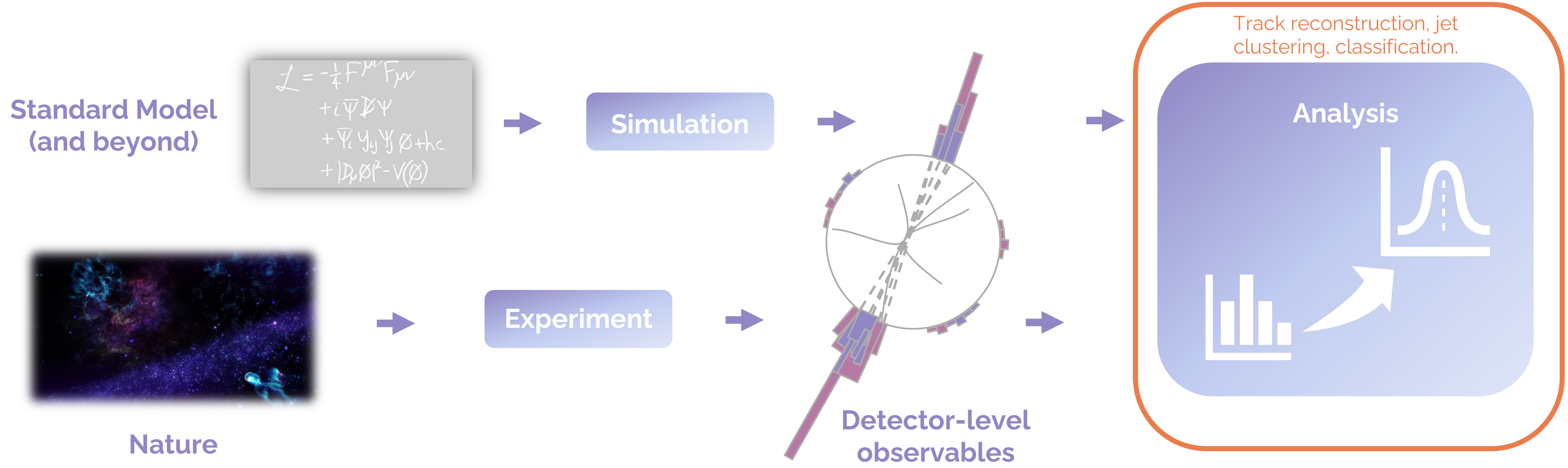
Wei, A. Y., Naik, P., Harrow, A. W., Thaler, J., **Quantum Algorithms for Jet Clustering** Phys. Rev. D101::094015 (2020

Delgado, A., Thaler, J., **Quantum Annealing for Jet Clustering with Thrust** arXiv: 2205.02814 (2022).

Pires, D., Omar, Y., Seixas, J. **Adiabatic Quantum Algorithm for Multijet Clustering in High Energy Physics** arXiv:2012.14514 (2020).

Anschuetz,, E., Funcke, L., et al., **Degeneracy Engineering for Classical and Quantum Annealing: A Case Study of Sparse Linear Regression in Collider Physics**, arXiv:2205.10375 (2022).

Data Analysis in High-Energy Physics



Variational Quantum Circuits as Machine Learning Models

- Parameterized circuit training for classification tasks such as event classification, track reconstruction.
- Advanced techniques such as data-reuploading, layer wise training.
- Deployed on IBM hardware, IonQ, CV platforms.

Terashi, K., Kaneda, M., Kishimoto, T., et al., **Event classification with quantum machine learning in high-energy physics**, Computing and Software for Big Science, 5(1) (2021).

Belis, V., Gonzalez-Castillo, S., Reisel, C., Vallecorsa, S., et al., **Higgs analysis with quantum classifiers**, EPJ Web of Conferences, 251:03070 (2021).

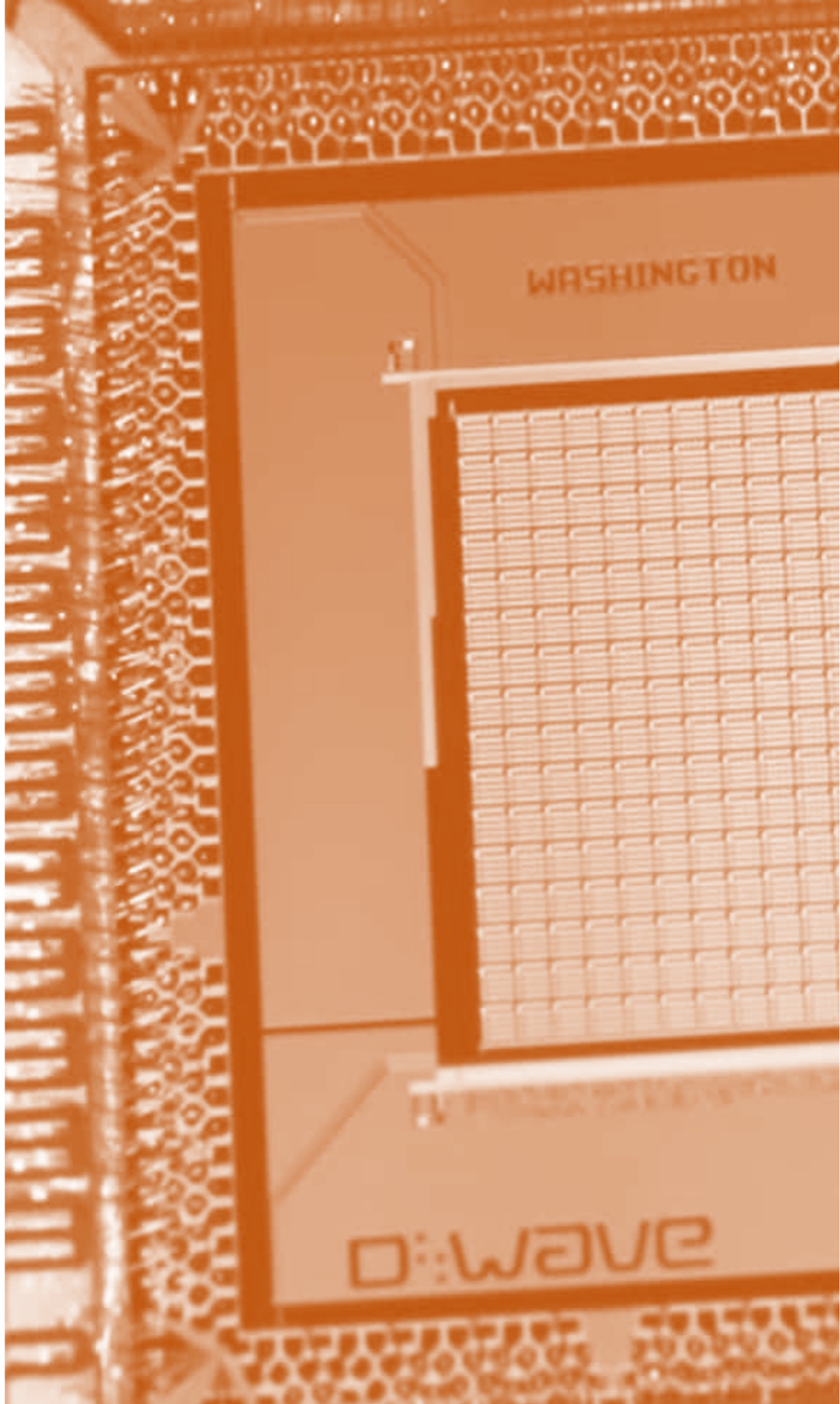
Peters, E., Caldeira, J., Ho, A., et al, **Machine learning of high-dimensional data n a noisy quantum processor,** npj Quantum Information, 7(1) (2021).

Gianelle, A., Koppenburg, P., Lucchesi, D., et al., **Quantum machine learning for b-jet identification**, arXiv:2202.13943 (2022)

Challenges

Quantum Annealing

- Large overhead associated with calculation of QUBO coefficients.
- Low connectivity among physical variables.
- Significant post-processing required, hyperparameter optimization.
- Problem decomposition tools lacking precision needed for HEP analysis.



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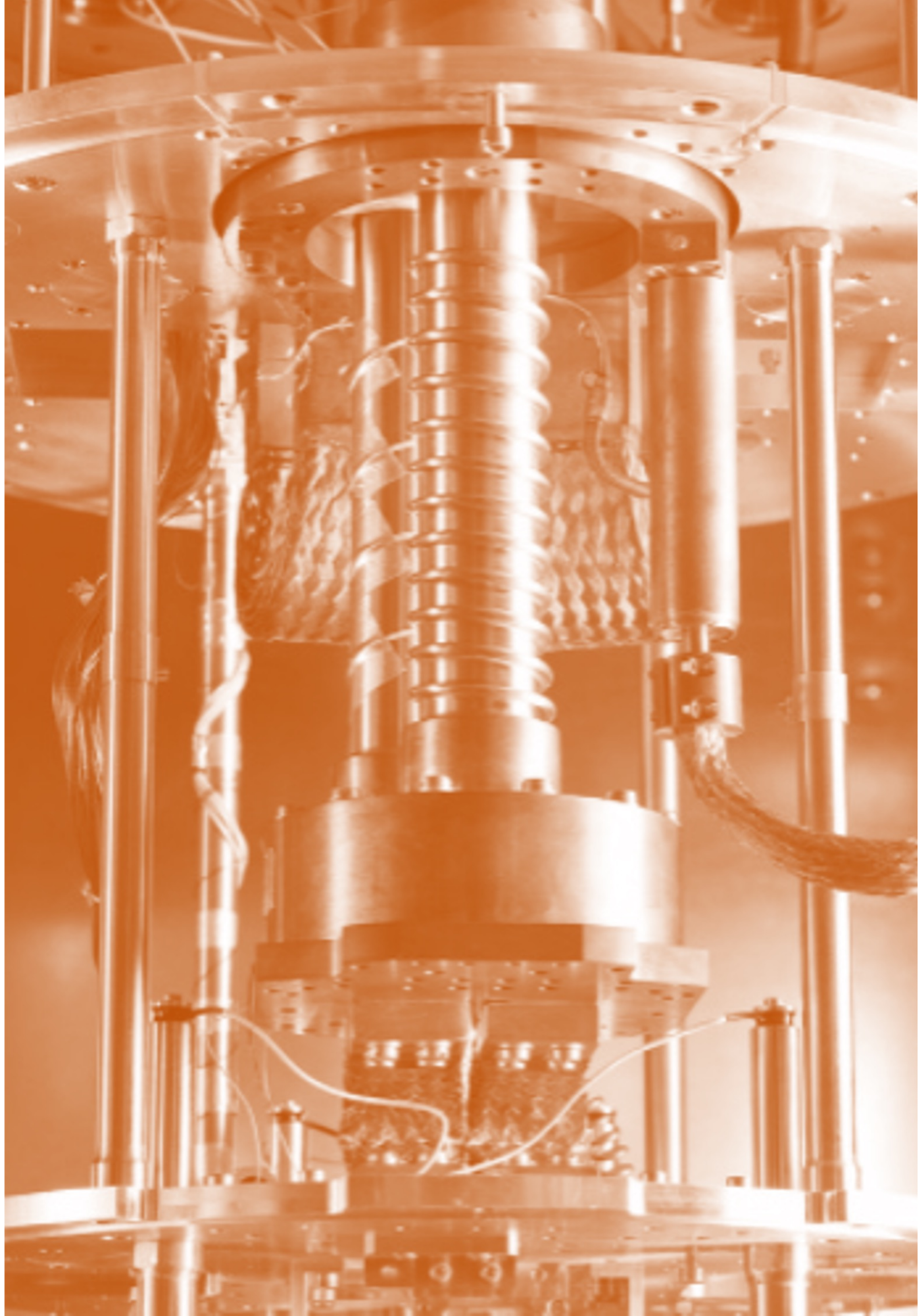
Gate-based Quantum Computing

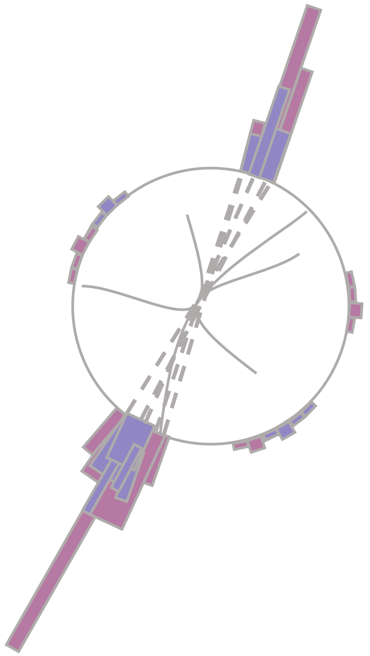
- Limited number of qubits, low connectivity.
- High overhead in embedding classical data into quantum states.
- Training limitations associated with cloud-based access.
- Scalable error correction techniques.

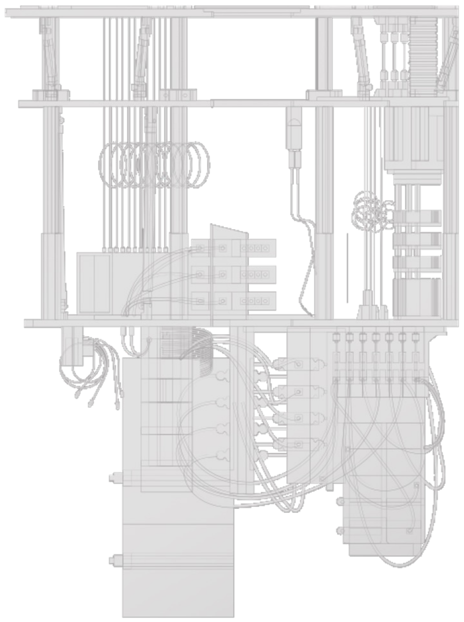


Outlook

★ **A large number of quantum computing applications to data analysis in HEP have been developed over the last decade.**

- *First applications on **D-Wave**, followed by circuit-based applications targeted for **IBM** hardware, mostly.*
- *CV continues largely unexplored.*
- *Huge development in the area of QML: largest kernel-based classifier (27 qubits) and generative model (12 qubits) to-date developed for HEP applications.*





Outlook

- ★ A large number of quantum computing applications to data analysis in HEP have been developed over the last decade.

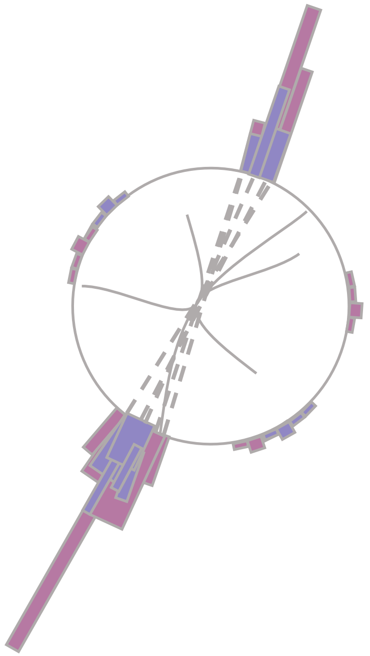
- ★ **Quantum Machine Learning will have an important role in quantum computing for HEP in the next decade.**
    - Most likely not revolutionary in the analysis of classical data.
    - But impactful in the analysis of quantum data, complementing quantum-enhanced searches for BSM physics and simulation of quantum systems.

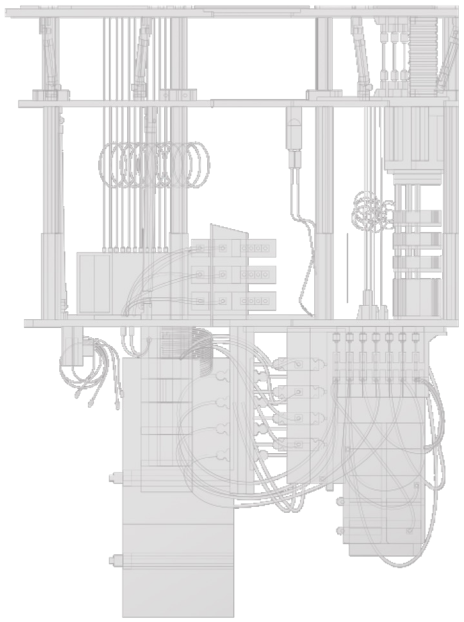
Outlook

- ★ A large number of quantum computing applications to data analysis in HEP have been developed over the last decade.

- ★ Quantum Machine Learning will have an important role in quantum computing for HEP in the next decade.

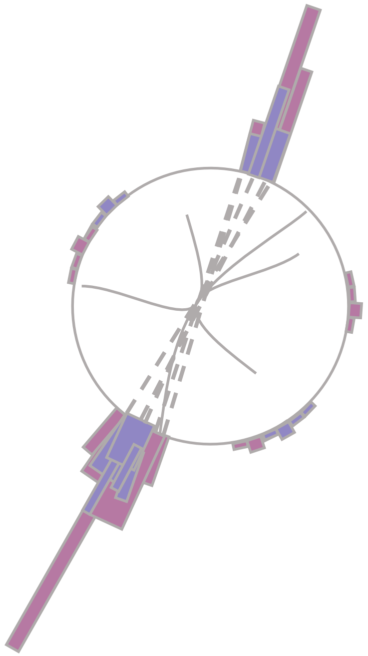
- ★ **There is still a lot of work to do.**
    - Understand the role of entanglement in model trainability,
    - Scalable error correction/mitigation techniques.
    - Understanding choice of Ansatz in model expressibility.
    - How to make better use of available Hilbert space, in terms of efficient measurements, metrics.

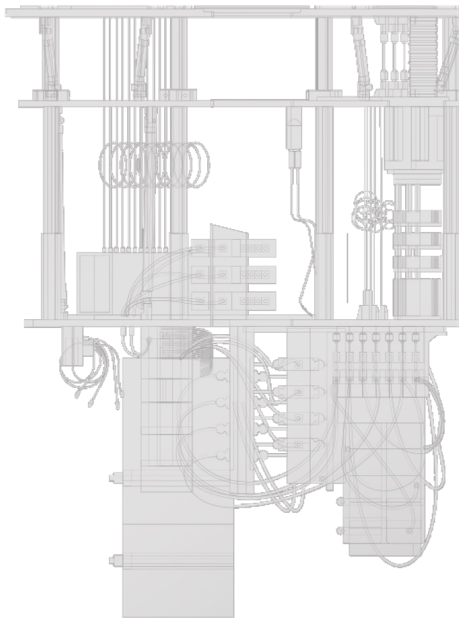




Outlook

- ★ A large number of quantum computing applications to data analysis in HEP have been developed over the last decade.
- ★ Quantum Machine Learning will have an important role in quantum computing for HEP in the next decade.
- ★ There is still a lot of work to do.
- ★ **Not covered on this talk:**
  - ★ Quantum-inspired models: Tensor networks as ML models.
  - ★ Storing an IceCube event into quantum memory - See Jeffrey Lazar's talk at the workshop or read the whitepaper ☺





Quantum Computing for Data Analysis in High-energy Physics*

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Thank you!