Track Reconstruction with Quantum Algorithms at High Energy Colliders

IHEP EPD Seminar, February 28, 2024

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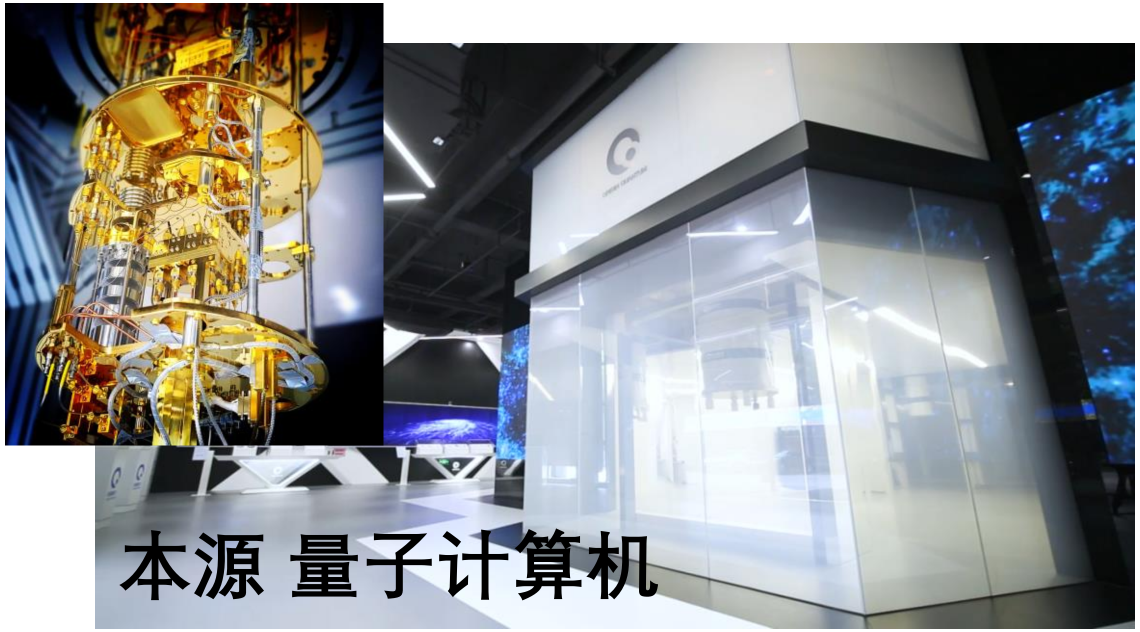
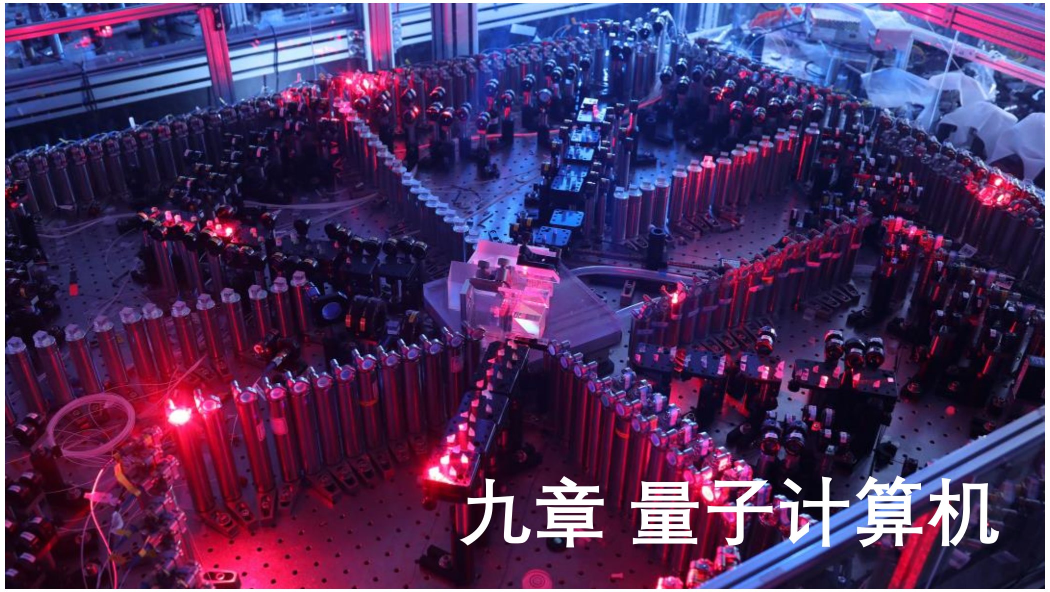
Quantum Computing





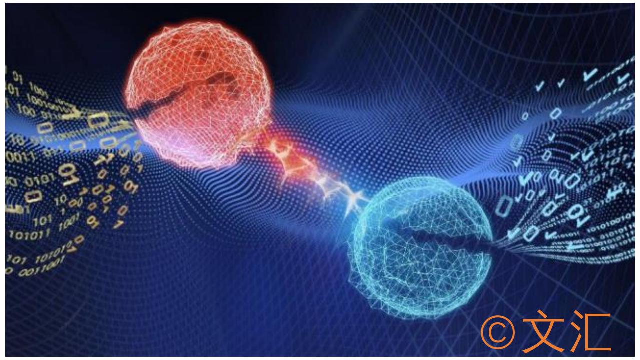
- Quantum computing is a technology of (near?) future
- R&D actively ongoing in various fields
- High energy physics in not an exception!


大数据
BIG
DATA

HEP


人工智能


量子化学


©文汇


现代农业
$N_2+3H_2 \rightleftharpoons 2NH_3$


金融


量子加密

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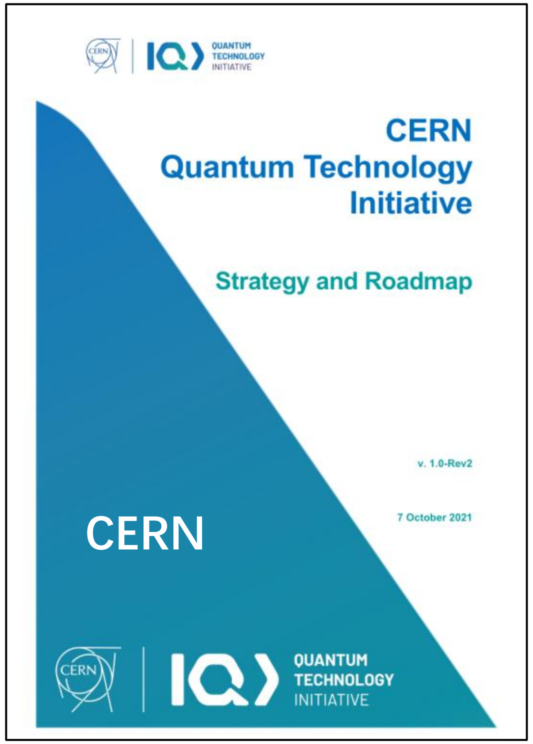
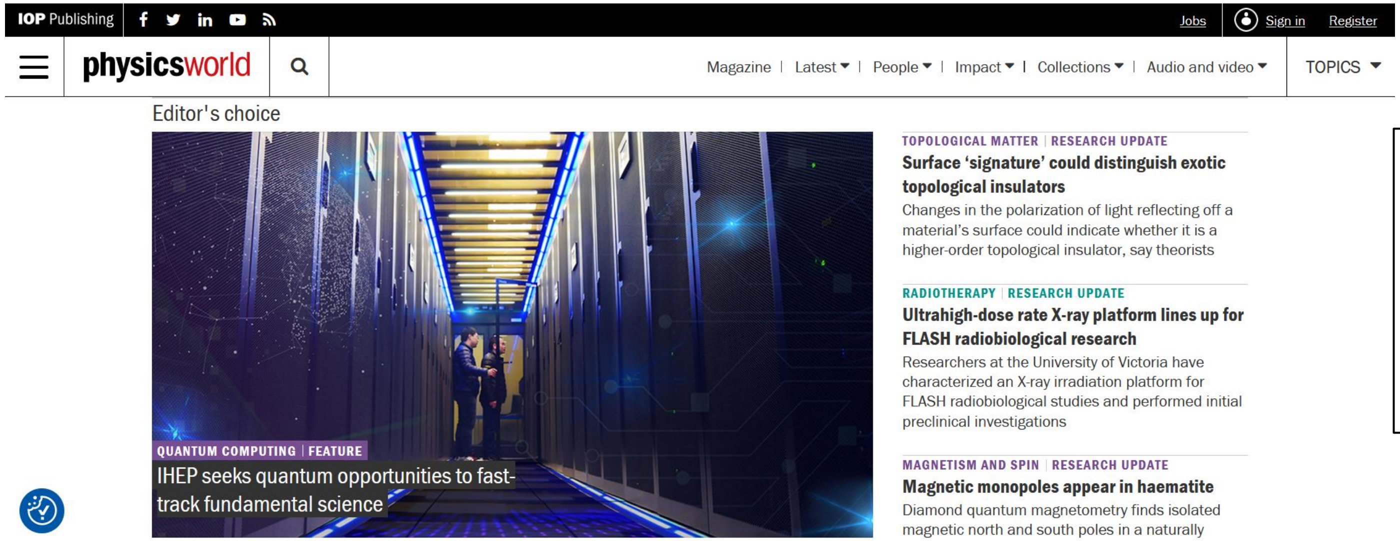
Quantum for High Energy Physics



- Rapidly gaining momentum in various countries. Various roadmaps presented in 2020’s. Dedicated research centers founded in many labs & univ.
- Including applications of quantum computing, algorithms & ML.

Quantum Computing @ IHEP



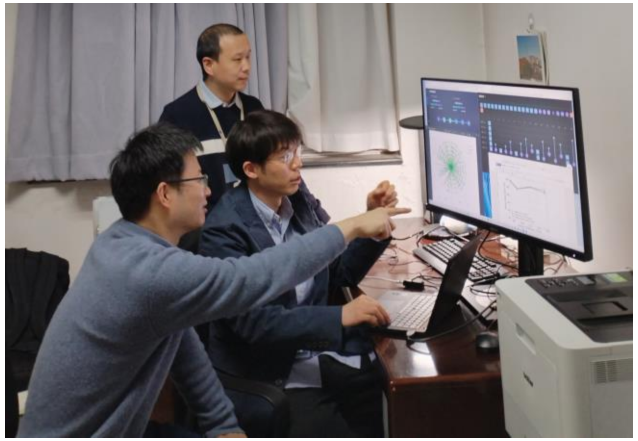
QUANTUM COMPUTING | FEATURE

IHEP seeks quantum opportunities to fast-track fundamental science

23 Feb 2024

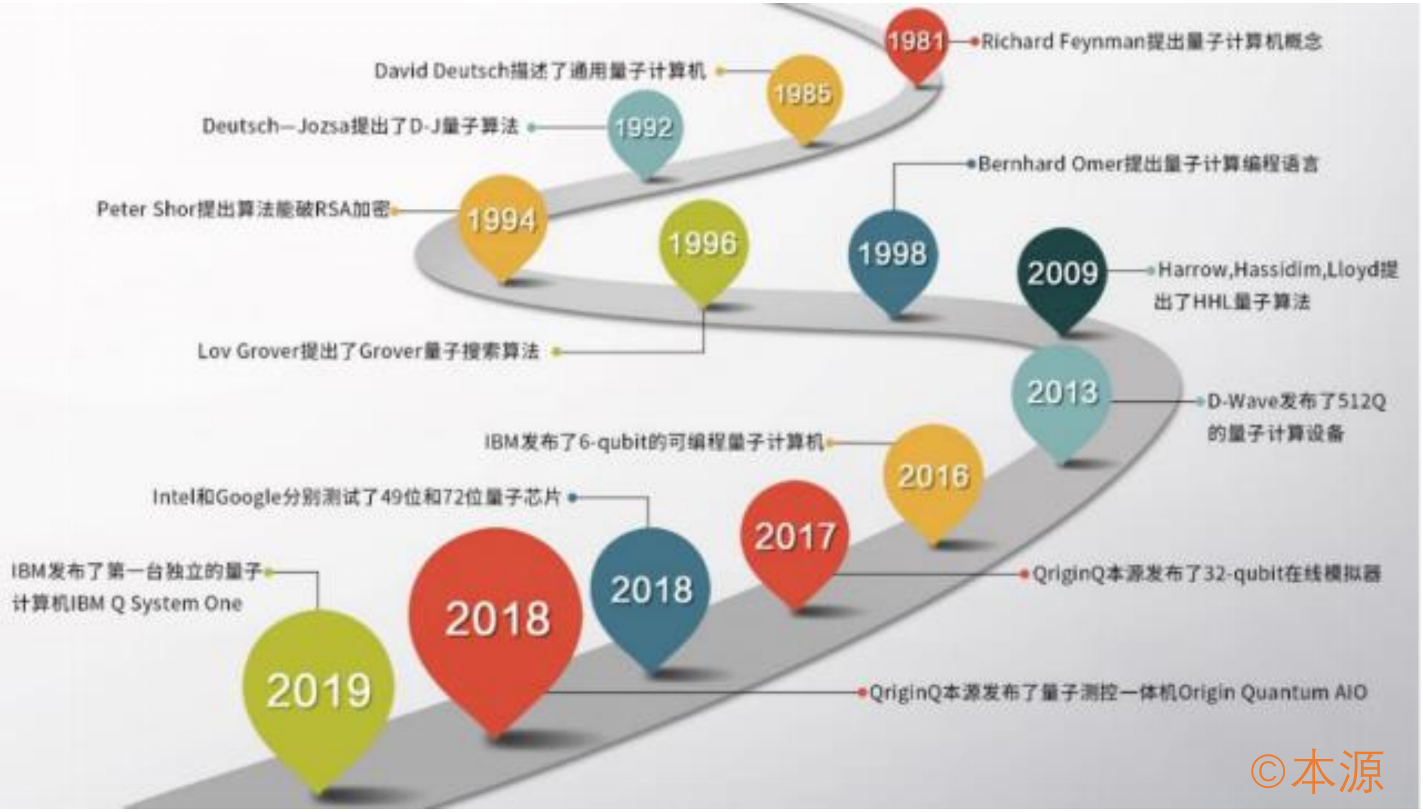
China's Institute of High Energy Physics (IHEP) in Beijing is pioneering innovative approaches in quantum computing and quantum machine learning to open up new research pathways within its particle physics programme, as Hideki Okawa, Weidong Li and Jun Cao explain

- **IHEP is leading quantum computing applications for HEP w/ domestic collaborators in China!**
- **Physics World invited us to describe the progress at IHEP (https://physicsworld.com/ we are now at the top page as the Editor's choice!)**



Myself, Jiaheng Zou, Xiaozhong Huang

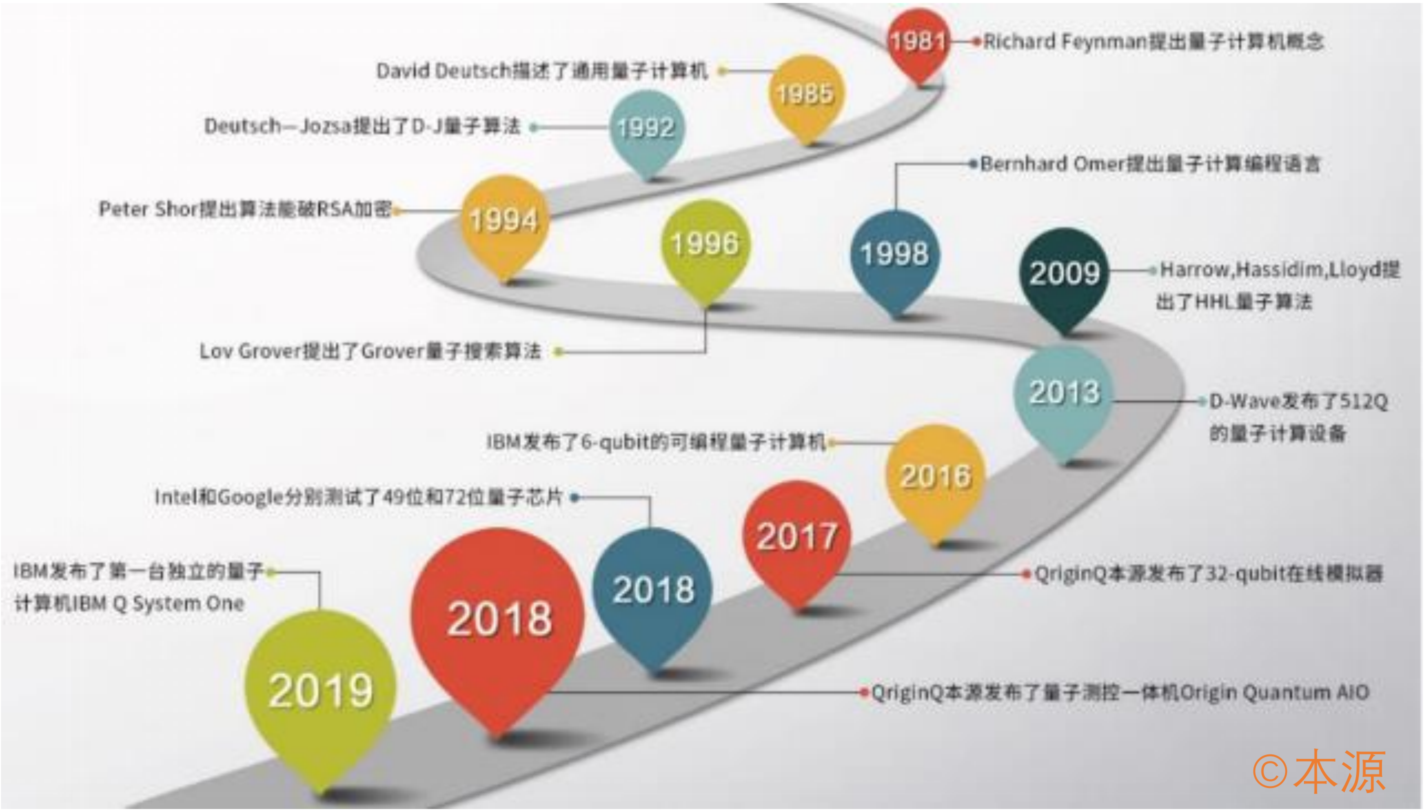
Brief History of Quantum Computing



- **1981: Feynman proposed quantum computing concept**

- "Now I explicitly go to the question of how we can simulate with a computer. . . the quantum mechanical effects . . . "
- "Can you do it with a new kind of computer — a quantum computer? Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind."

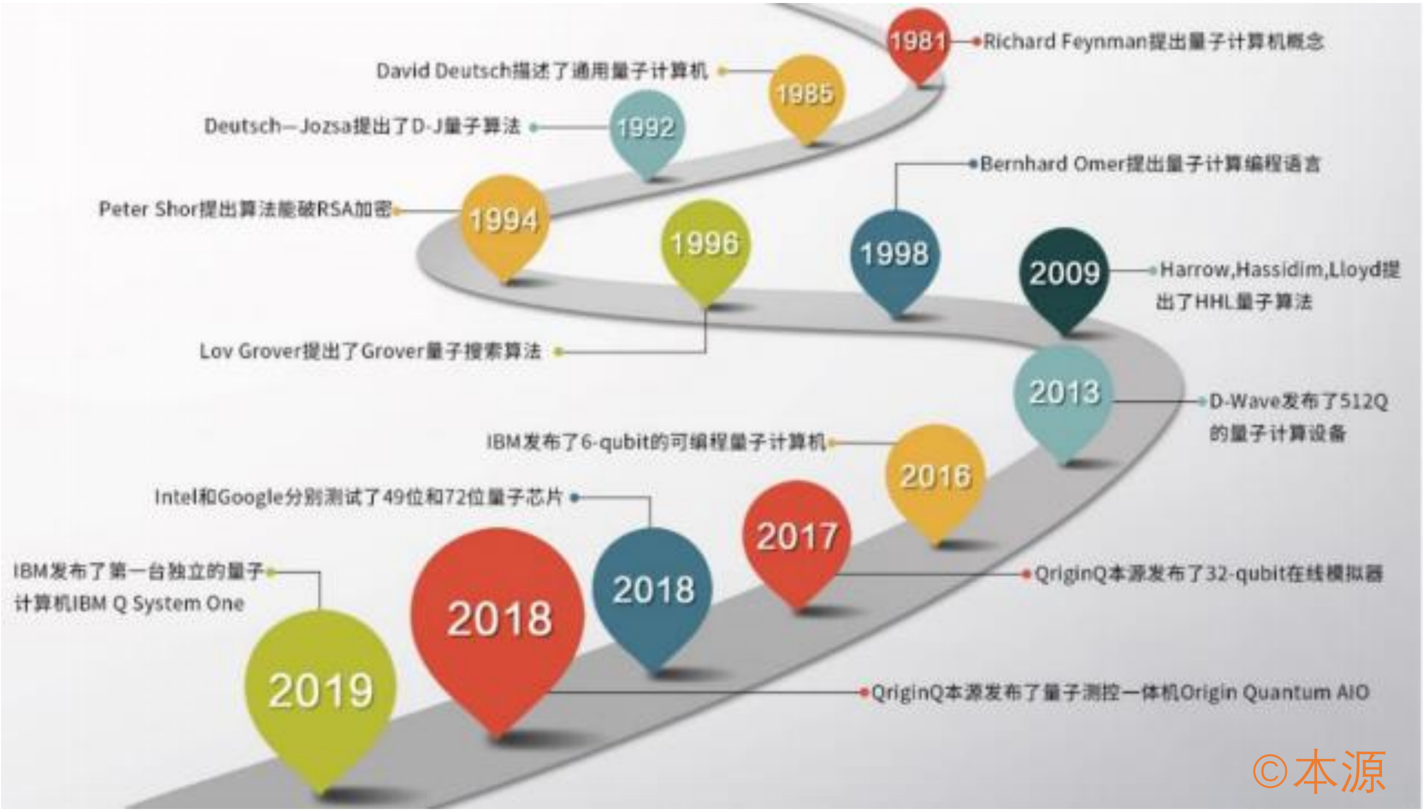
Brief History of Quantum Computing



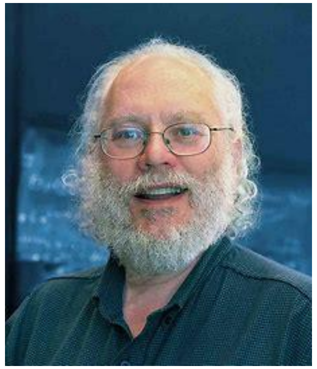
- **1985: Deutsch described the first universal quantum computer**

- Proposed current quantum qubit model
- **Can pursue the same computation as the classical Turing machine → the universal quantum computers**
- **Attracted numerous computer scientists to the quantum computation field**

Brief History of Quantum Computing

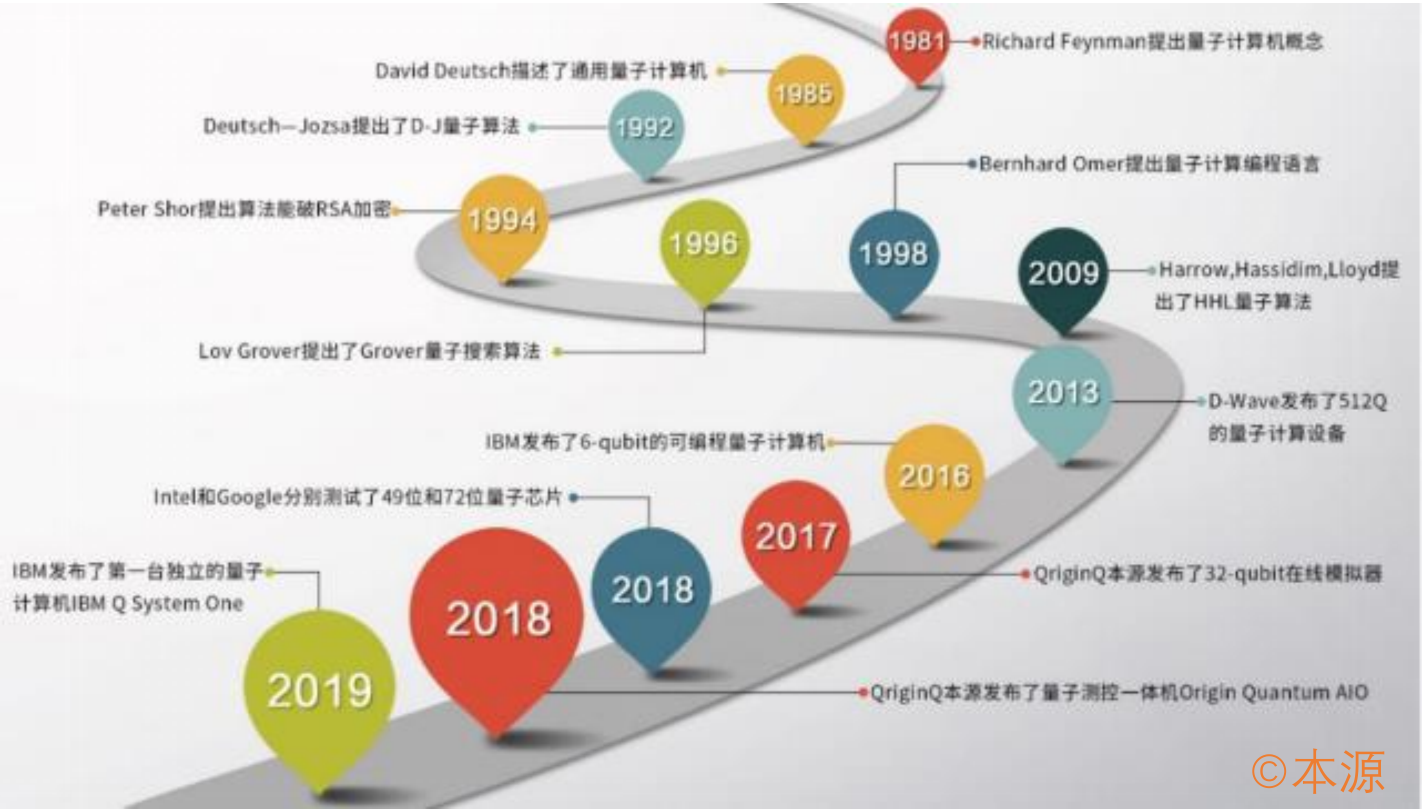


- 1994: Shor proposed algorithm to crack RSA encryption



- Encryption relies on factorization and requires exponential computation time to solve algorithm
- **Shor’s algorithm can solve in polynomial time**

Brief History of Quantum Computing



- 2013: D-Wave released quantum annealing machine
- Dawn of practical quantum computing era

Annealing (Analog) vs Gates (Digital)

Annealing

- Utilizes adiabatic quantum evolution to seek for the ground state of a Hamiltonian
  - Only applicable to optimization problems
- Implemented in D-Wave Systems.
- “Quantum-inspired” annealing emulator by Fujitsu, HITACHI, etc.
  - Useful for developing algorithms

Gates

- Utilizes quantum logic gates
- General purposed
- Most quantum computers in follow this approach
- 海外: IBM, Google, Xanadu, etc. (D-Wave is also joining)
- 中国：本源, 国盾, 量子院quafu, 百度etc.

量子霸权，量子优势 Quantum Supremacy/Advantage

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

Received: 22 July 2019

Accepted: 20 September 2019

Published online: 23 October 2019

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Nature vol. 574, p. 505–510 (2019)

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量子霸权，量子优势 Quantum Supremacy/Advantage

RESEARCH

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2*], Hui Wang[1,2*], Yu-Hao Deng[1,2*], Ming-Cheng Chen[1,2*], Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2†], Jian-Wei Pan[1,2†]

Quantum computers promise to perform certain tasks that are believed to be intractable to classical computers. Boson sampling is such a task and is considered a strong candidate to demonstrate the quantum computational advantage. We performed Gaussian boson sampling by sending 50 indistinguishable single-mode squeezed states into a 100-mode ultralow-loss interferometer with full connectivity and random matrix—the whole optical setup is phase-locked—and sampling the output using 100 high-efficiency single-photon detectors. The obtained samples were validated against plausible hypotheses exploiting thermal states, distinguishable photons, and uniform distribution. The photonic quantum computer, *Jiuzhang*, generates up to 76 output photon clicks, which yields an output state-space dimension of 10^{30} and a sampling rate that is faster than using the state-of-the-art simulation strategy and supercomputers by a factor of ~10^{14}.

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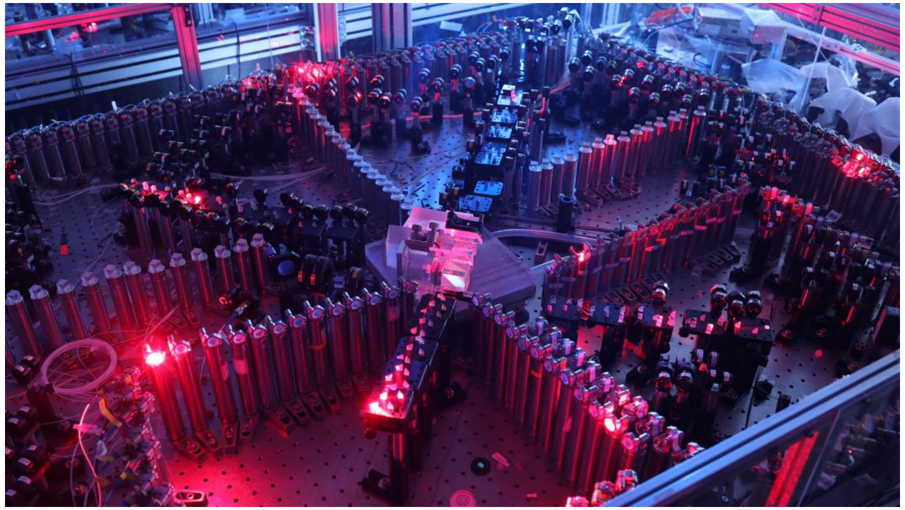
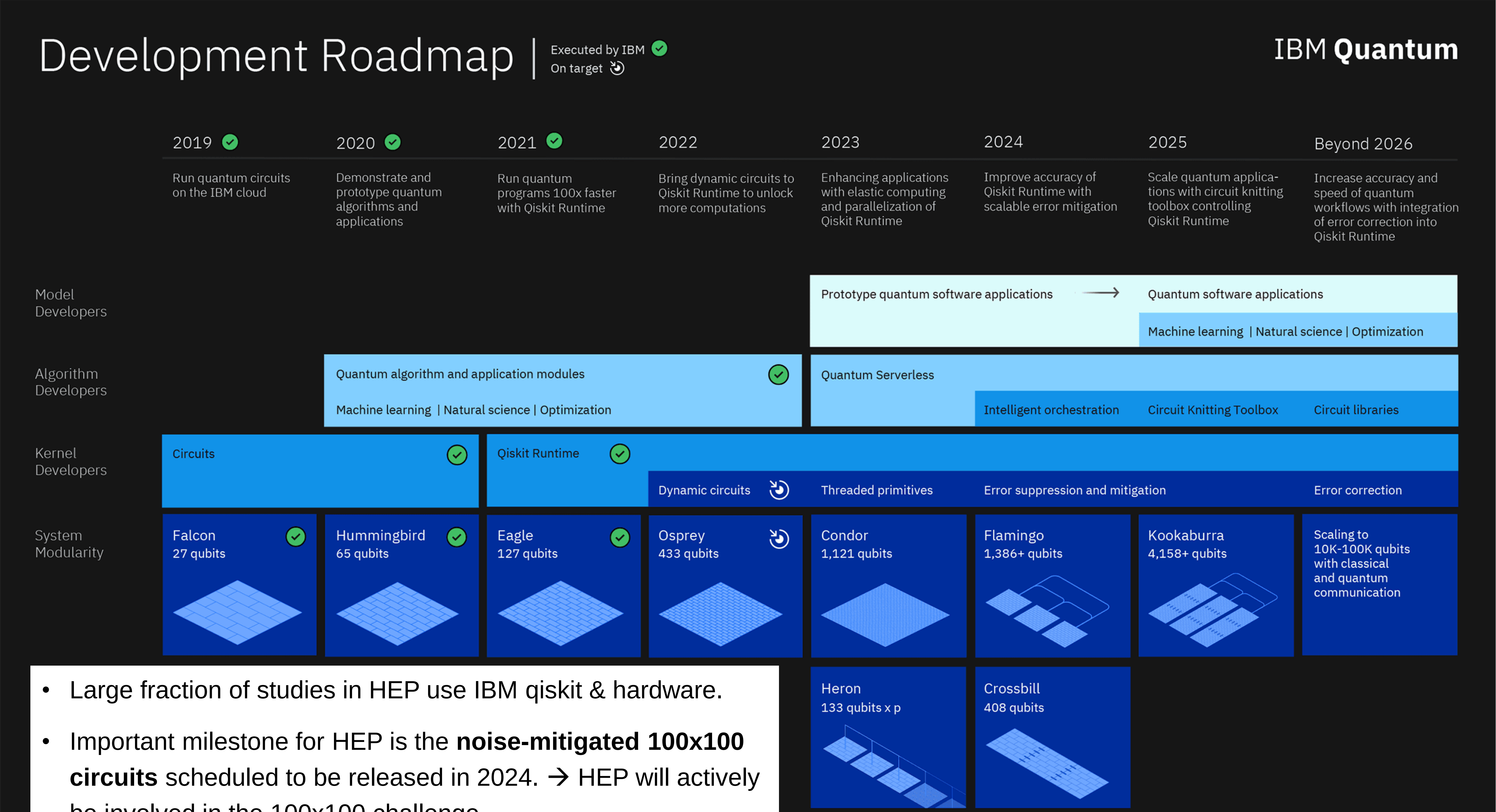
Science 370, 1460–1463 (Dec. 2020)

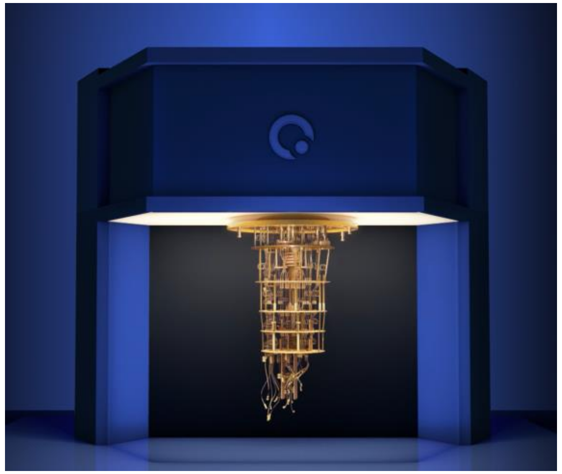
九章 量子计算机





- Large fraction of studies in HEP use IBM qiskit & hardware.
- Important milestone for HEP is the **noise-mitigated 100x100 circuits** scheduled to be released in 2024. → HEP will actively be involved in the 100x100 challenge

Chinese Quantum Cloud Examples



From Origin Quantum website

本源 (Origin Quantum)

- Using superconductors.
- 72 qubit machine available now.
- Various libraries available for QML.

北京量子院 Quafu

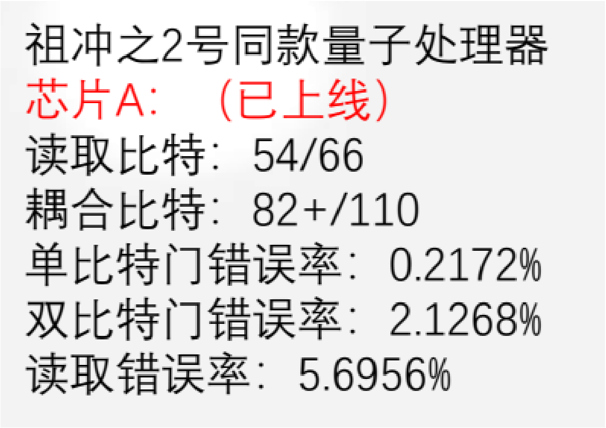
- Using superconductors.
- Fully free: 10, 18, 21, 136 qubits

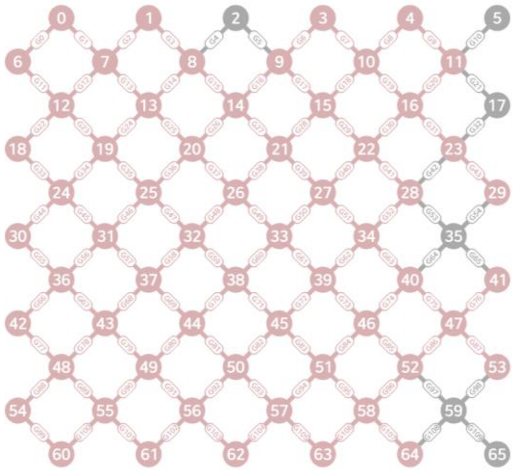
From quafu website

Chinese Quantum Cloud Examples

国盾量子 (Quantum Tek)

- Optical quantum computers.
- 66 qubits, 110 couplers





From 梁福田‘s slides

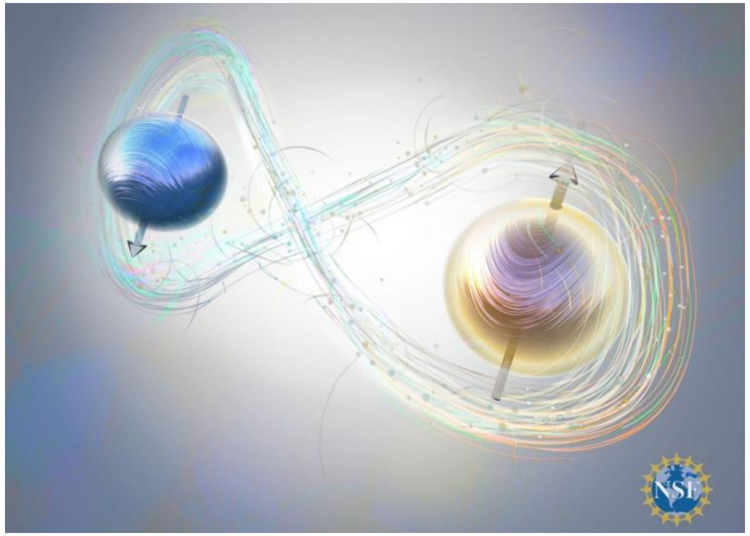
百度 量易伏

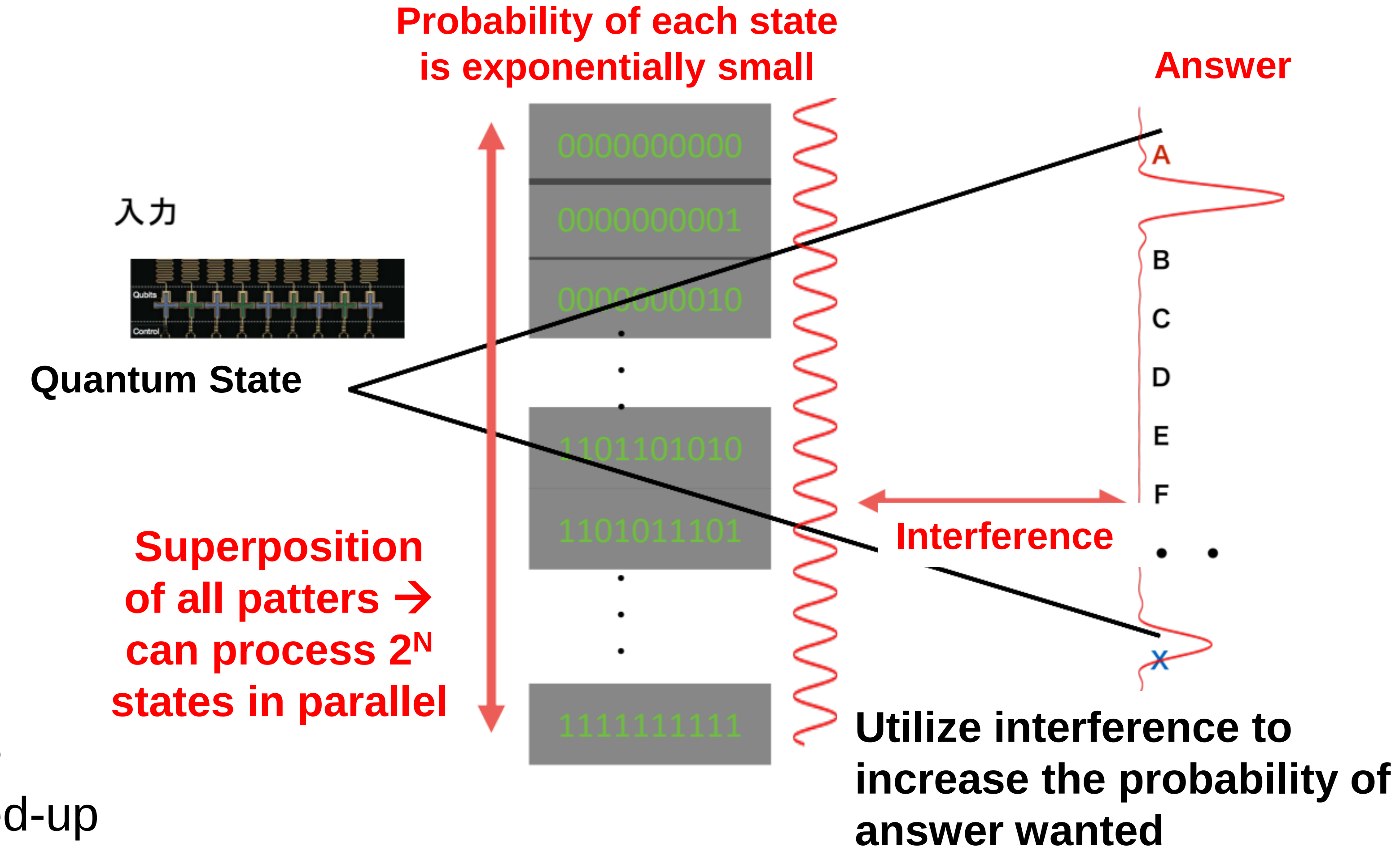
- 1, 8, 10 qubits
- Superconductors or Ion-trap

From 刘树森’s slides

Why Quantum Computing?

Modified from ©QunaSys

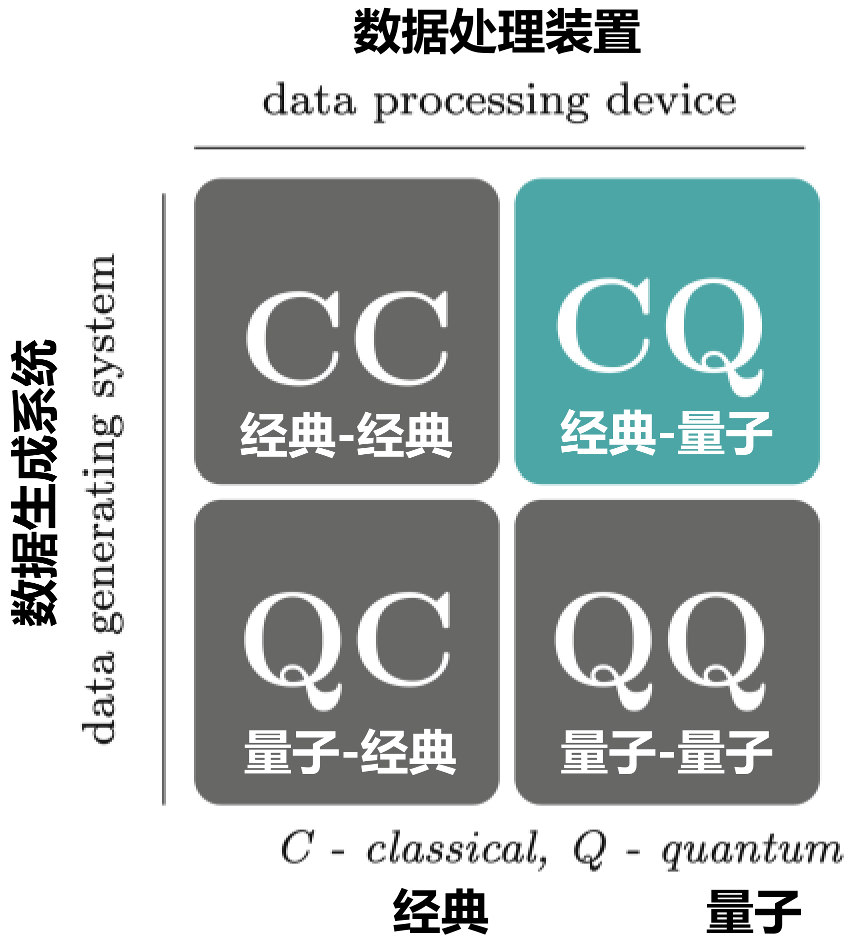




- Through superposition, entanglement, interference (& tunneling), quantum computers could bring in exponential speed-up

Quantum Computer + Machine Learning

- **Quantum computer + machine learning → Quantum machine learning (QML)**
  "the best of both worlds"?
- Why do we bother? → Rich Hilbert space, superposition, entanglement (& tunneling) could lead to improvement in learning data
- 4 types of QML exist
- However, quantum advantage is not yet fully established in practical implementations (starting to see some signs though).



Today's Menu: Tracking w/ CQ, CC

CQ approach (classical data + quantum computer)

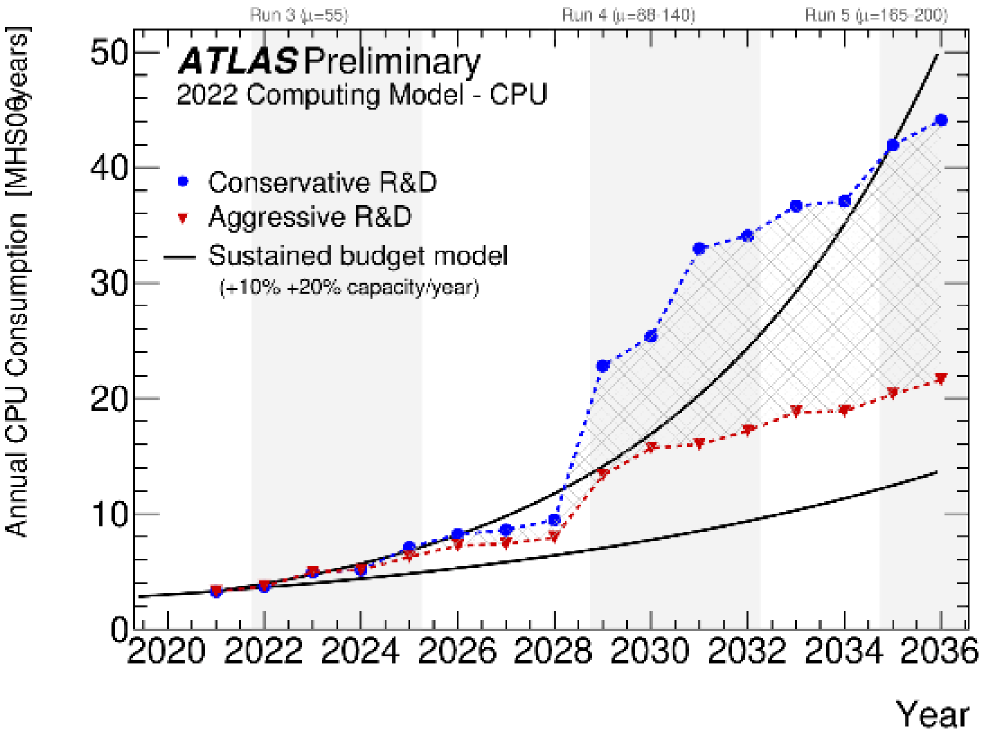
1. **H. Okawa**, "Charged particle reconstruction for future high energy colliders with Quantum Approximate Optimization Algorithm," Springer Communications in Computer and Information Science, 2036 (2024) 272–283, arXiv:2310.10255

NEW!

CC approach (fully classical but quantum-inspired algorithm)

2. **H. Okawa**, Q.-G. Zeng, X.-Z. Tao, M.-H. Yung, "Quantum Annealing Inspired Algorithms for Track Reconstruction at High Energy Colliders," arXiv:2402.14718 (2024).

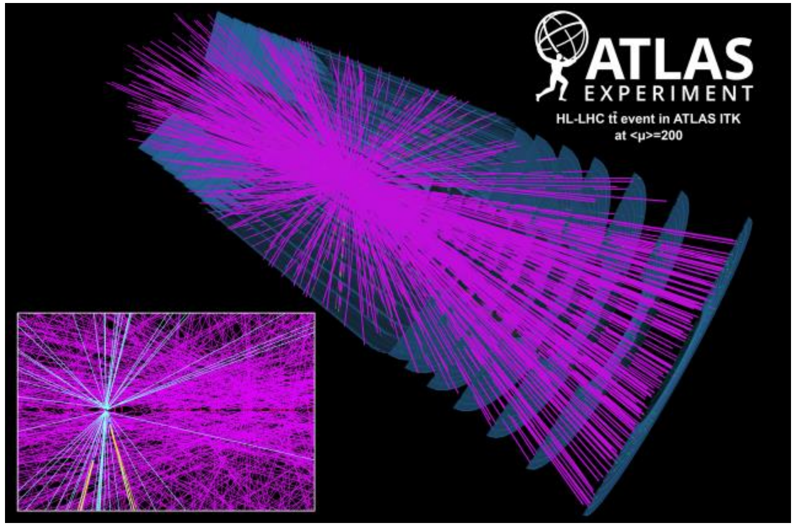
Why Quantum Computing for HEP?



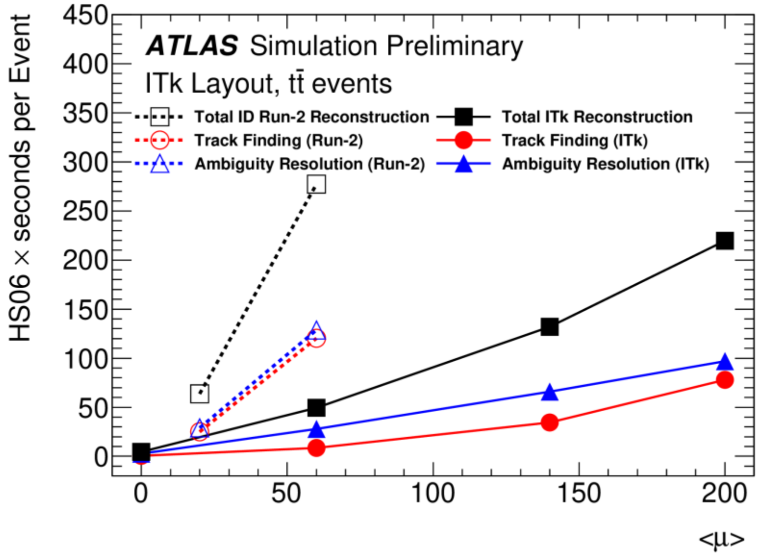
- At the HL-LHC, **we will enter the "Exa-byte" era. Annual computing cost will increase by a factor of 10-20**
- **Without various innovations, the experiment will not be able to operate.** GPUs and other state-of-the-art technologies will be the baseline at the HL-LHC.
- **Quantum computing may bring another "leap".**

- **Tracking is the highest CPU consuming reconstruction task.**
- Tackling these challenges will also be useful for future colliders: e.g. CEPC & SppC

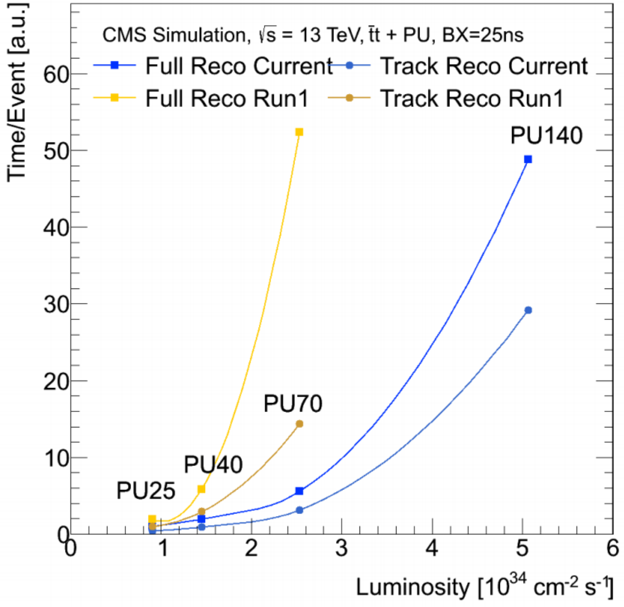
Track Reconstruction at LHC & HL-LHC



ATL-PHYS-PUB-2019-041



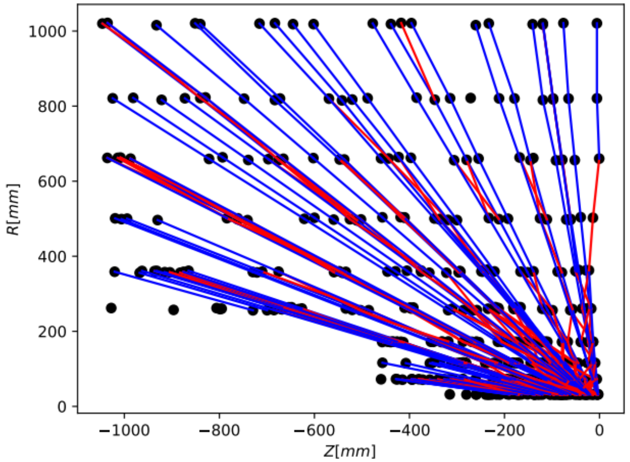
https://cds.cern.ch/record/1966040

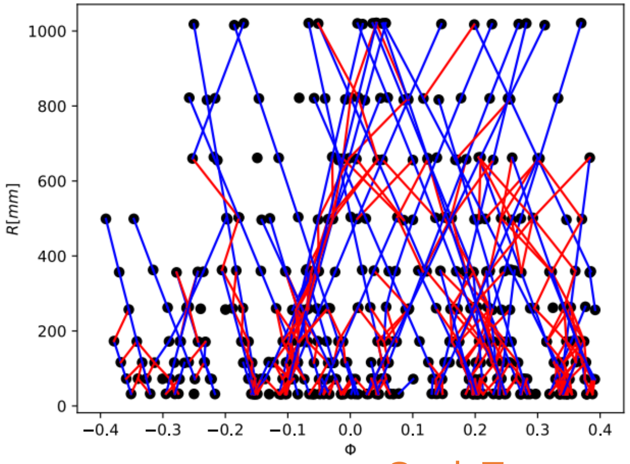


	Run 1	Run 2	HL-LHC
μ	21	40	150-200
Tracks	~280	~600	**~7-10k**

- At the HL-LHC, additional interactions per bunch crossing becomes exceedingly high & **CPU time increases exponentially with more pileup**.
- GPU & ML-based approaches are actively investigated, but quantum ML may play an important role.

Classical ML Approaches





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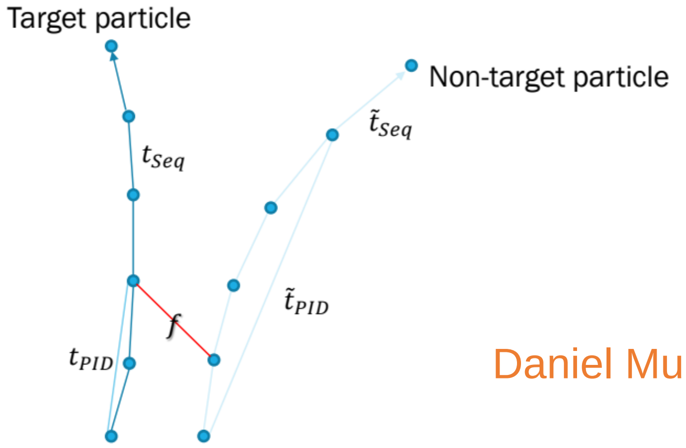
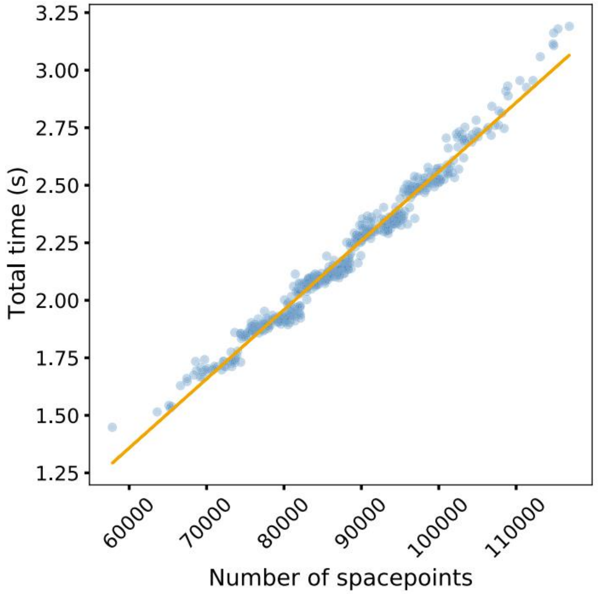


Daniel Murnane

- Graph neural network (GNN) is actively investigated in the LHC [Project Exa.TrkX] & BES-III communities.
  - There are also studies using CNN & Point Net at BES-III
- Silicon hits can be regarded as "**nodes**" & connected segments as **"edges"**
- Computing time scales linearly with number of tracks

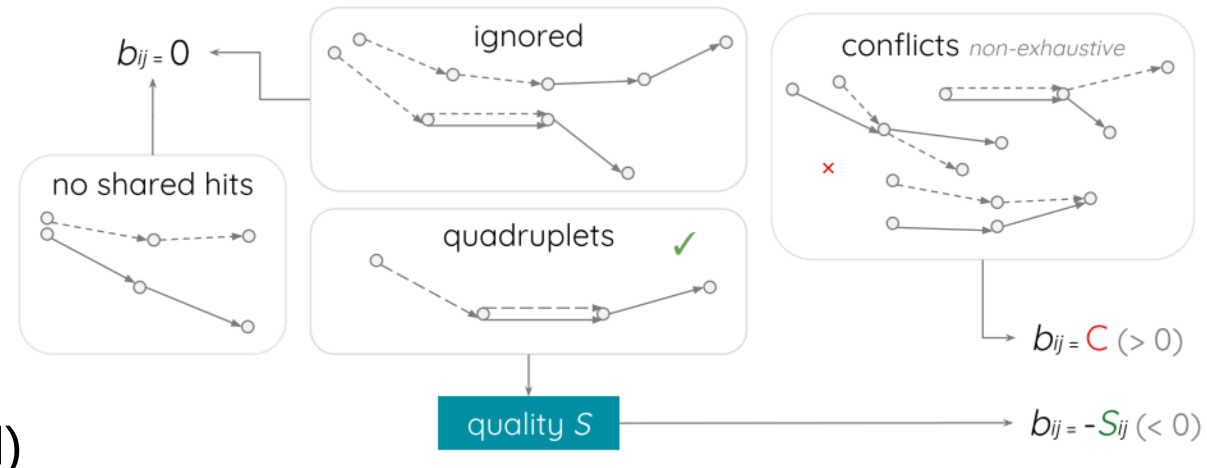


Quantum Approach: QUBO

- Tracks are formed by connecting silicon detector hits: e.g. triplets (segments w/ 3 hits).

$$O(a,b,T) = \underbrace{\sum_{i=1}^{N} a_i T_i}_{\text{Quality of triplets}} + \underbrace{\sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j}_{\text{Compatibility b/w triplet pairs}}$$

F. Bapst et al. Comp. Soft. Big Sci. 4 (2019) 1.

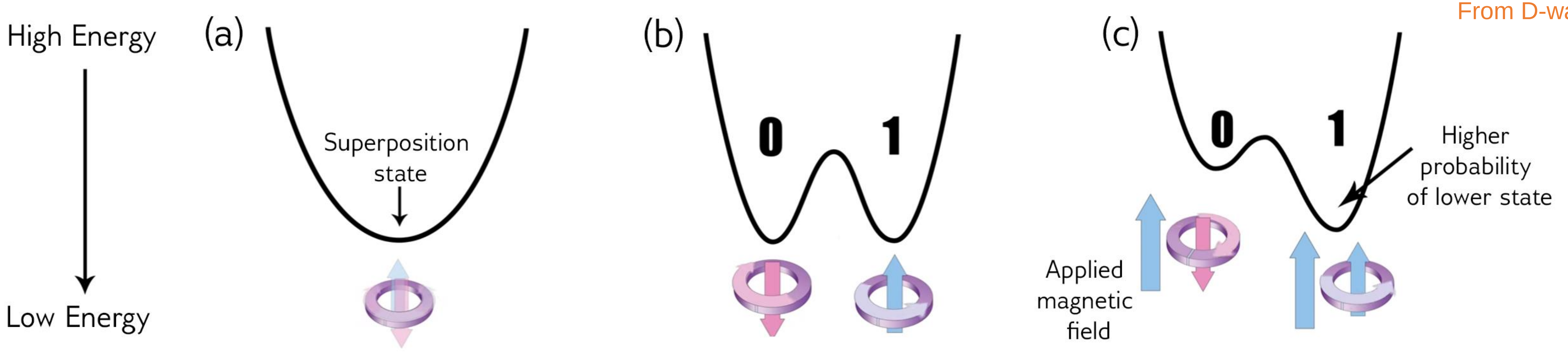


b_{ij} = 0 (if no shared hit)
= 1 (if conflict)
= $-S_{ij}$ (if two hits are shared)

- Triplets are connected to reconstruct tracks & it can be regarded as a **<u>quadratic unconstrained binary optimization (QUBO)</u>** problem.
- **Minimizing QUBO is equivalent to searching for the ground state of the Hamiltonian.**

Quantum Annealing Approach

From D-wave website

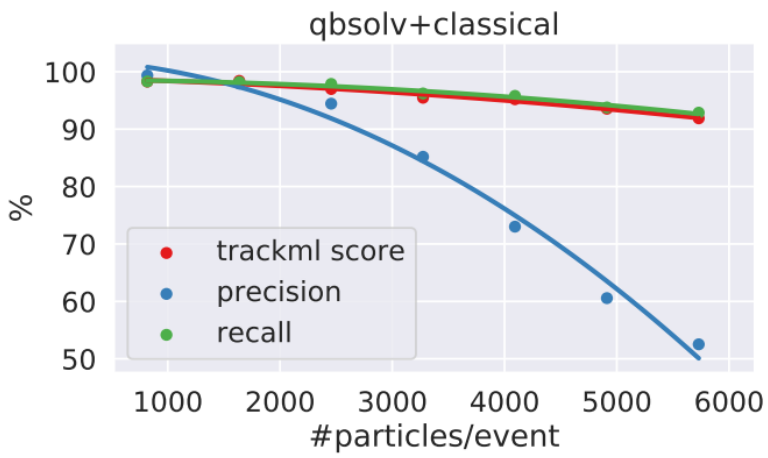


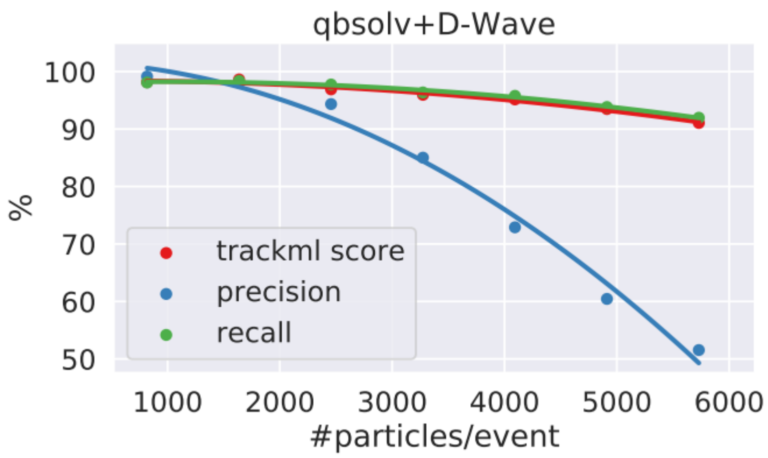
- Quantum annealer looks for the global minimum of a given function with quantum tunneling: a natural machine to search for the ground state of a Hamiltonian.
- D-Wave currently provides 5000+ qubit service (1200+ qubits, 10000+ couplers available in Jan. 2024).
- Pros: High number of qubits available (concept fundamentally different from quantum gates).
- Cons: Can only run QUBO problems. Also, not suitable for very small minimum energy gaps, as the computing time explodes to remain adiabatic.

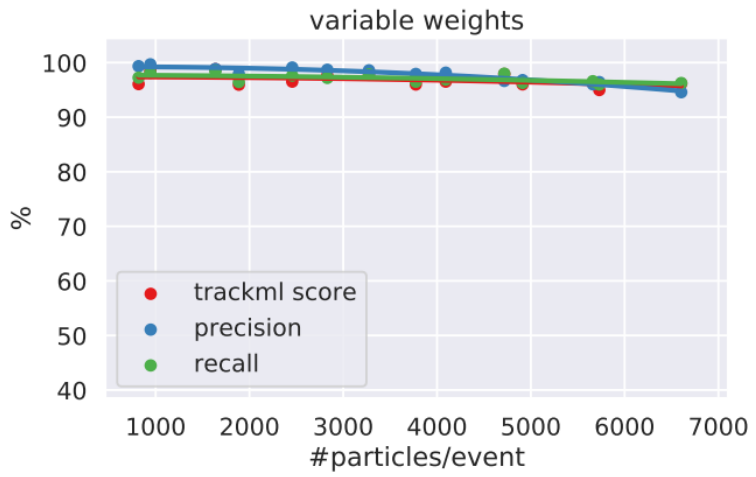
F. Bapst et al. Comp. Soft. Big Sci. 4 (2019) 1 & L. Linder, Master Thesis at EPFL.

Previous Studies w/ Q. Annealing

- Previous studies w/ D-Wave machine show that efficiency is almost stable w/ # of particles, but purity (precision) degrades. → later resolved w/ QUBO optimization.
- Simulator provides consistent results w/ hardware.
- Quantum annealers are generally powerful, but not suitable for very small minimum energy gaps, as the computing time explodes to remain adiabatic.
  → Gate computers, in particular, QAOA has an advantage for such cases.





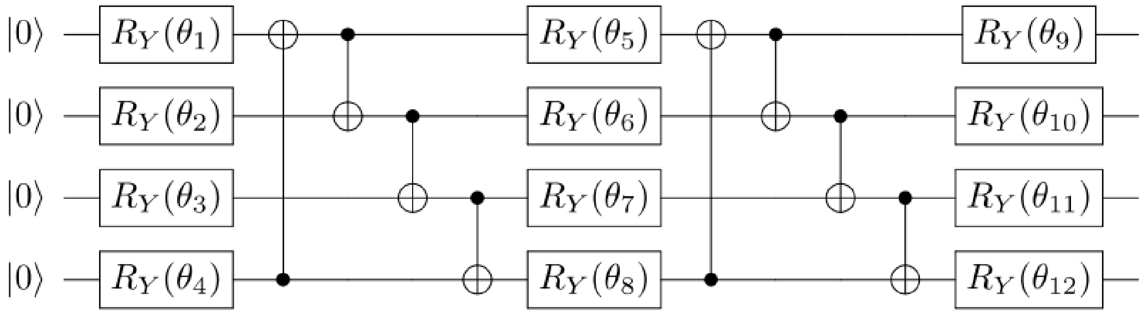


Running on Quantum Gates

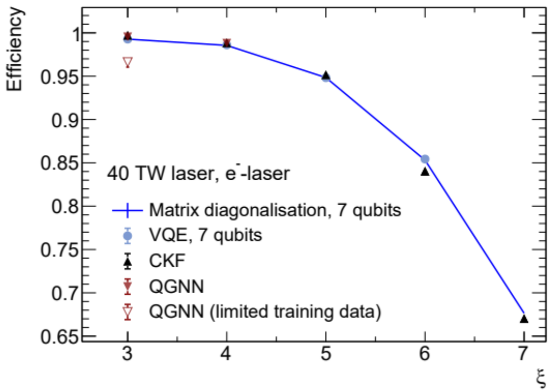
- QUBO can be mapped to Ising Hamiltonian and be solved using Variational Quantum Eigensolver (VQE) or Quantum Approximate Optimization Algorithm (QAOA) w/ quantum gates.

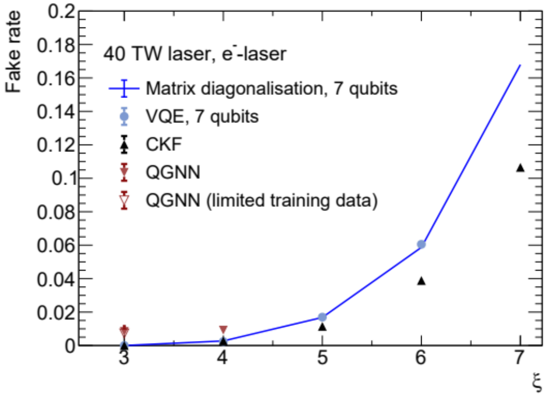
$$\mathcal{H} = -\sum_{n=1}^{N}\sum_{m<n} \bar{b}_{nm}\sigma_n^x\sigma_m^x - \sum_{n=1}^{N}\bar{a}_n\sigma_n^x$$

- Previous LUXE studies considered VQE w/ TwoLocal ansatz w/ R_Y gates & circular CNOT entangling pattern w/ IBM (A. Crippa et al., arXiv:2304.01690, L.Funcke et al., arXiv:2202.06874)
- **QAOA did not perform well & optimization was left for future studies. → A scope of this talk**



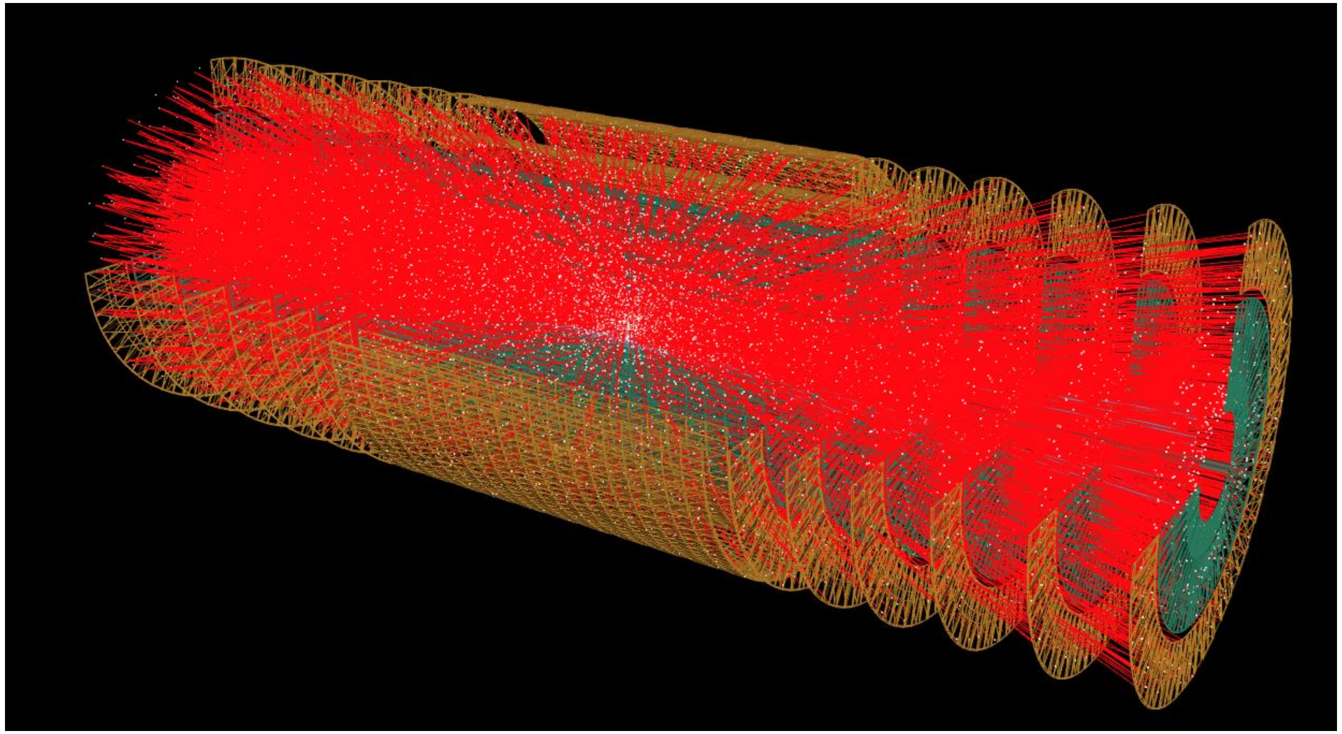
Only 4 qubits drawn for simplicity





Dataset (TrackML)

- TrackML is an open-source dataset prepared for TrackML Challenges (a competition hosted by CERN & Kaggle).
- It is **designed w/ HL-LHC conditions (200 pileup) & run w/ fast simulation (e.g. noise, inefficiency, parametrized material effects, etc.)**
- Continues to be useful for individual studies including quantum tracking.



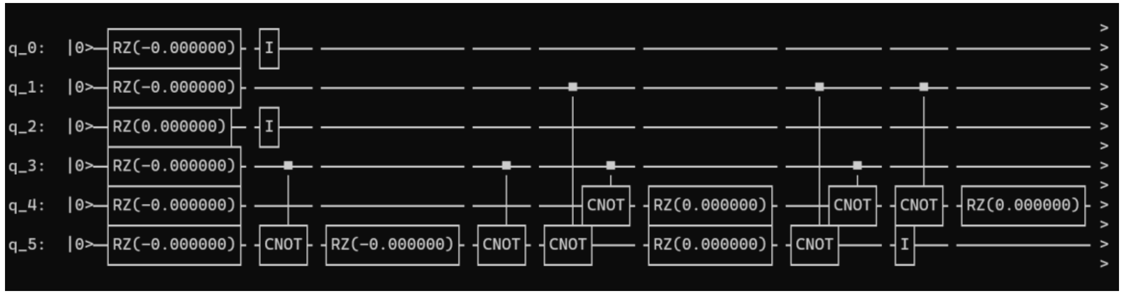
CQ Approach (经典数据+量子计算)

H. Okawa, Springer Communications in Computer and Information Science, 2036 (2024) 272–283, arXiv:2310.10255

QAOA in Origin Quantum (本源)

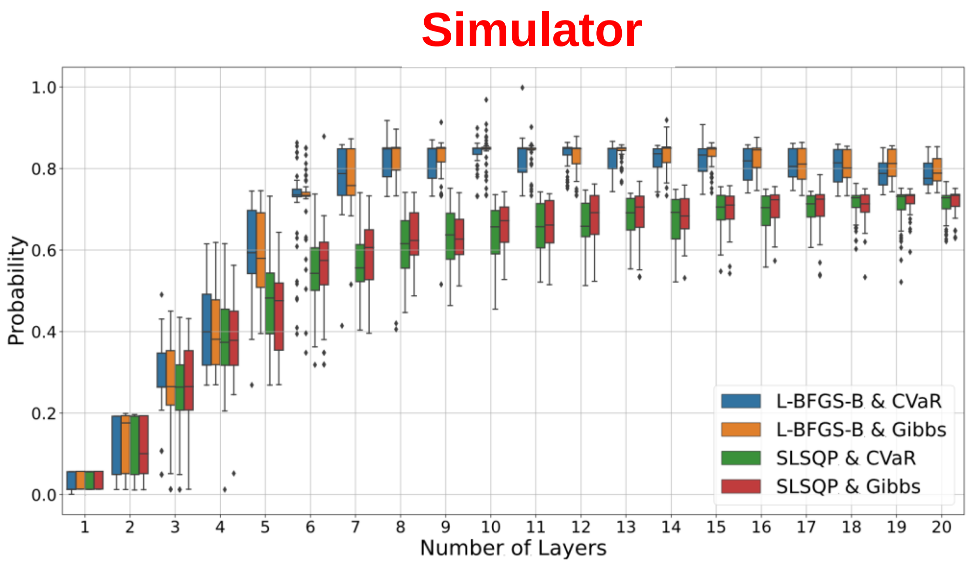
- VQE & QAOA libraries implemented in pyqpanda-algorithm by OriginQ (本源).
- Adopts **Quantum Alternative Operator Ansatz** for QAOA.

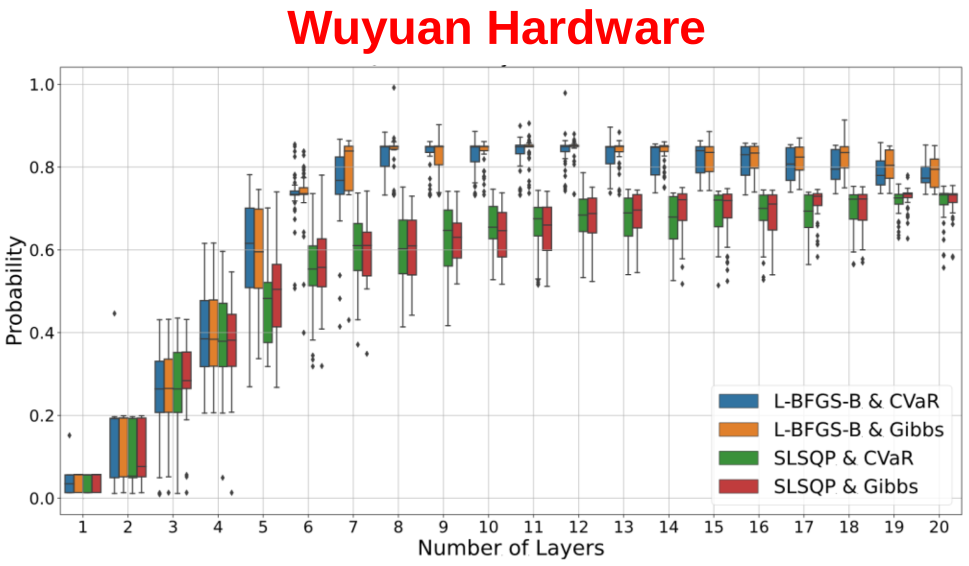
An example of circuits from the actual run



- Can utilize CVaR loss function (P. Barkoutsos et al., Quantum, 2020, 4: 256) or Gibbs optimization
- **6 qubit machine (Wuyuan 悟源)** is used for the real hardware computation in this talk.

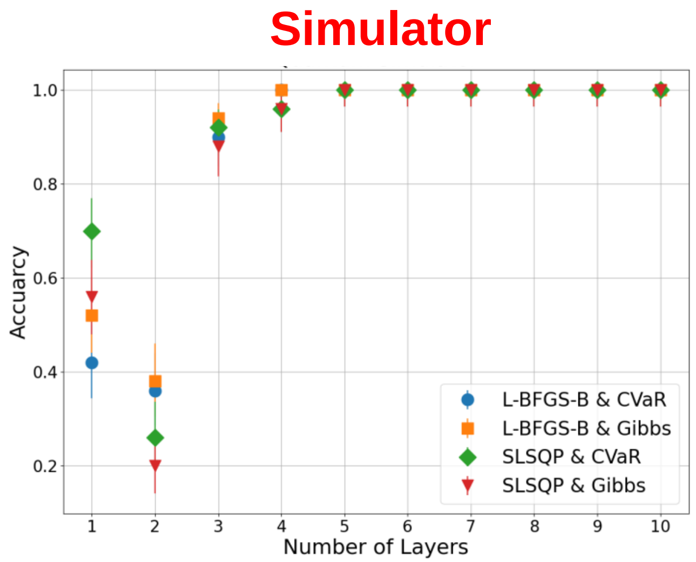
QAOA Optimization

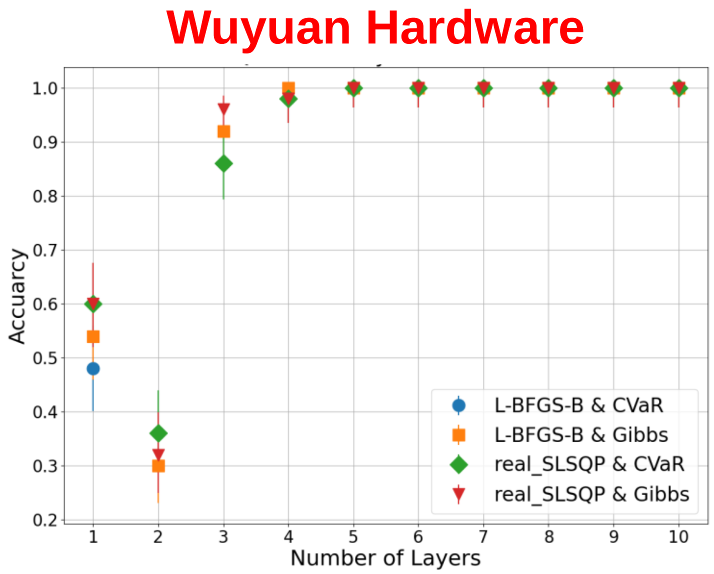




- **QAOA does not perform well w/ shallow layers, but provides good performance with more layers. <u>Compatible performance b/w hardware & simulator.</u>**
- L-BFGS-B optimizer is better than SLSQP. TNC has degraded performance & not shown here.
- No significant difference w/ CVaR or Gibbs loss function.
- **Probability saturates around 7 layers for L-BFGS-B cases.**

QAOA Accuracy

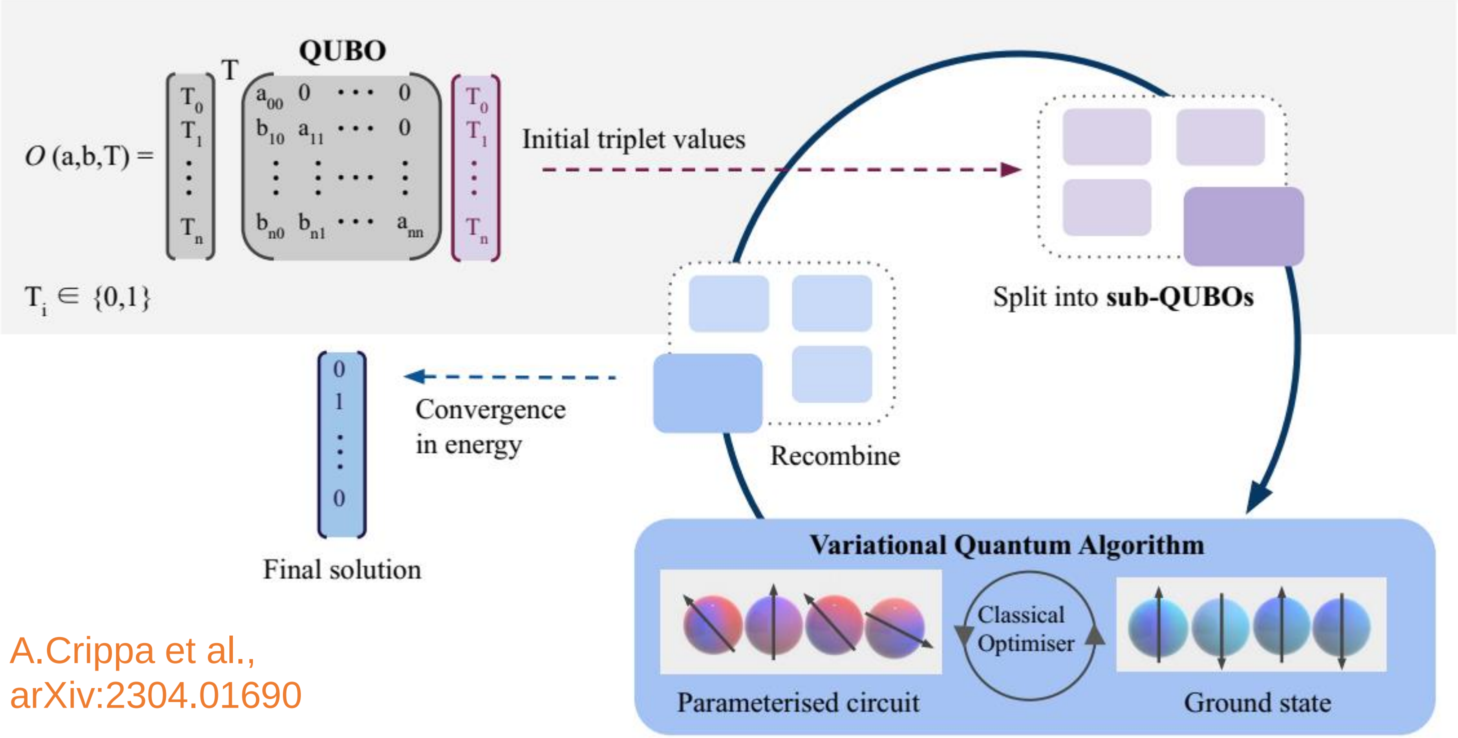




- **<u>Note that the probability is NOT the accuracy of QAOA.</u>**
- A single job runs multiple measurements, ranks the answers by probability & select the highest probability state as answer.
- **<u>The accuracy already reaches 100% within the statistical uncertainty at 5 layers.</u>**
- For further studies, a conservative choice of 7 layers is used.

Sub-QUBOs

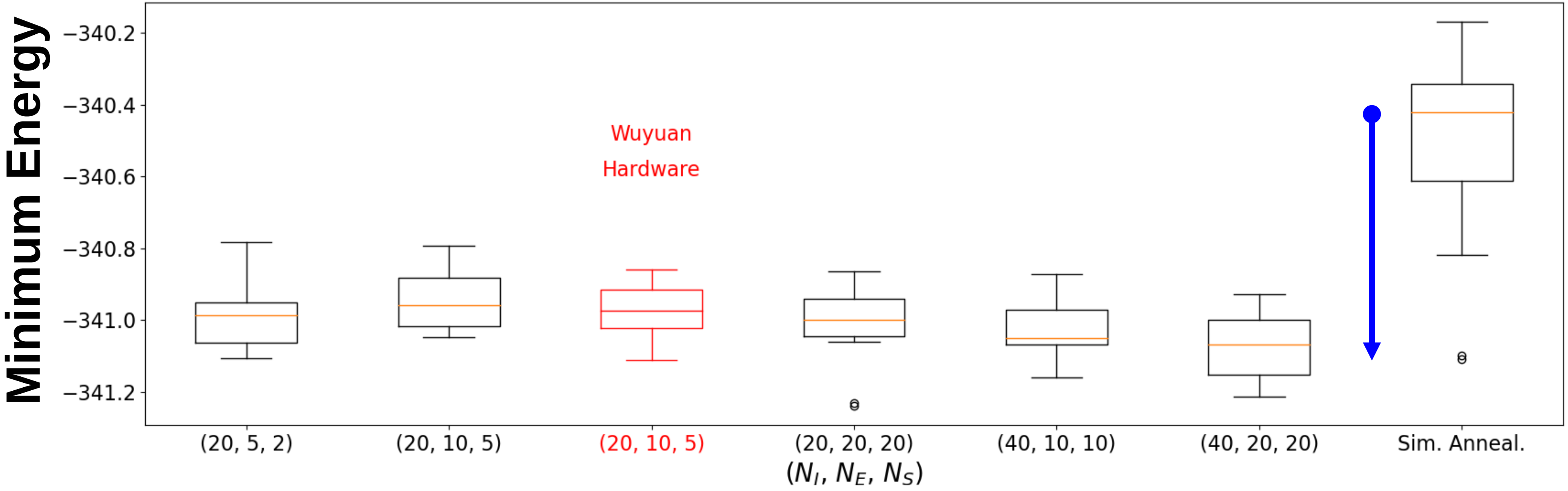
- **Number of qubits required is determined by the number of triplet candidates** → Obviously cannot cover the full QUBO [$O(10^2 \text{x} 10^2 \sim 10^4 \text{x} 10^4)$] for tracking in the NISQ era
- QUBO is split into sub-QUBOs of size **6x6 to match with OriginQ hardware.**



A.Crippa et al., arXiv:2304.01690

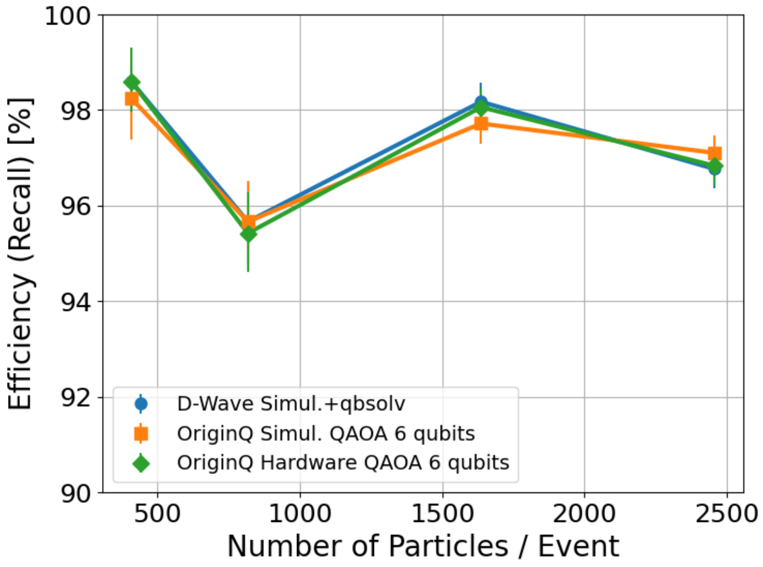
- There are various sub-QUBO algorithms proposed: qbsolv (now in dwave-hybrid library), for example.
- I adopted **a sub-QUBO method using multiple solution instances** from Y. Atobe, M. Tawada, N. Togawa, IEEE Trans. Comp. 71, 10 (2022) 2606.

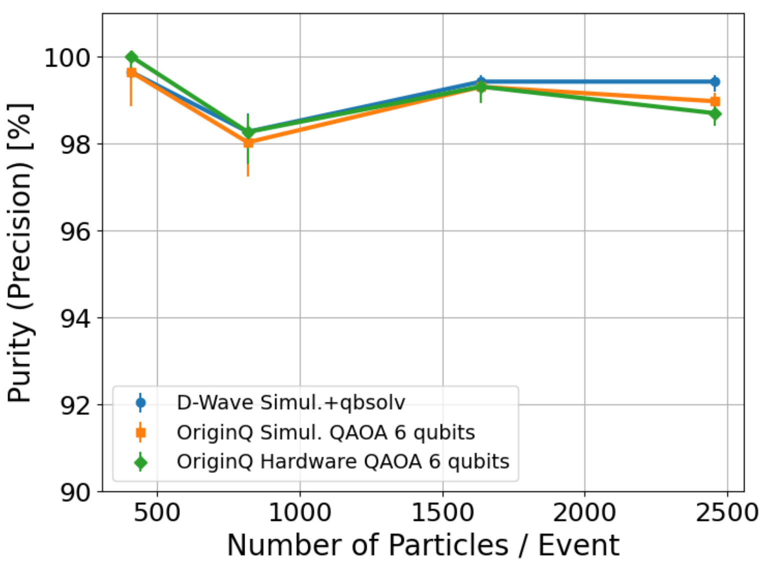
Preliminary sub-QUBO Results

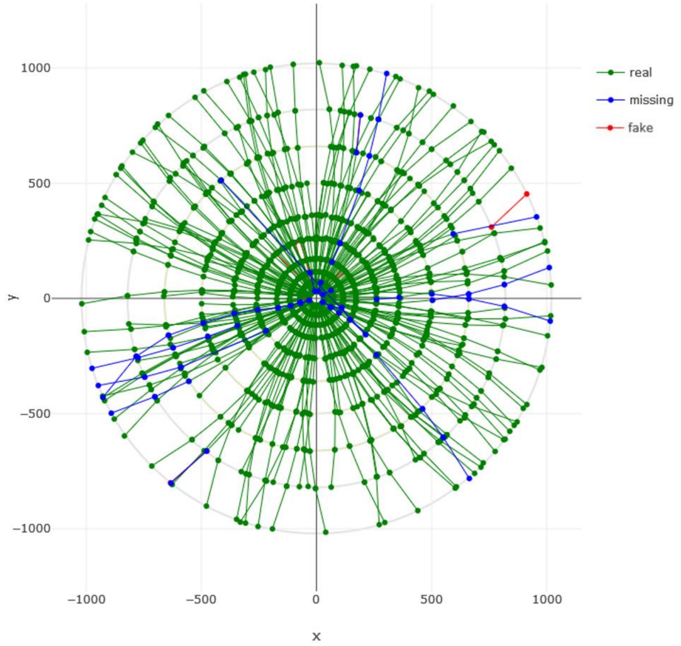


- Ran measurements to compare the performance and stability. 7 layers used in QAOA.
- No significant dependence on sub-QUBO model parameters (N_I, N_E, N_S) & **compatible performance between OriginQ simulator & actual hardware!**
- **Visible improvement w/ sub-QUBO compared to the simulated annealing only!**

WIP: Triplet Efficiency & Purity





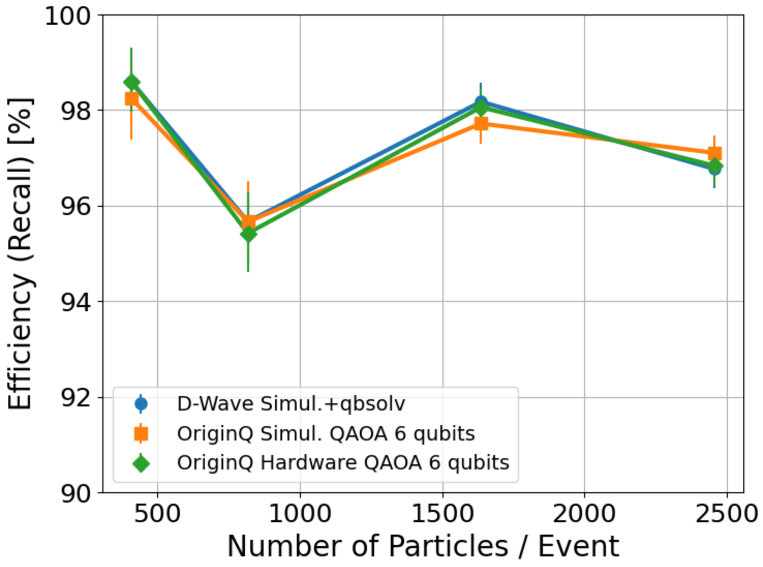


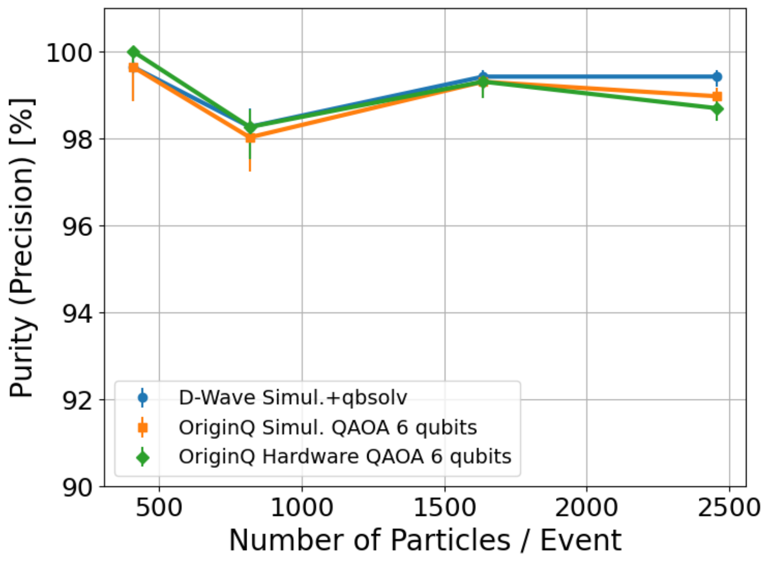
$$\text{Efficiency} = \frac{TP}{TP+FN} = \frac{\#\text{ of matched reconstructed doublets}}{\#\text{ of true doublets}},$$

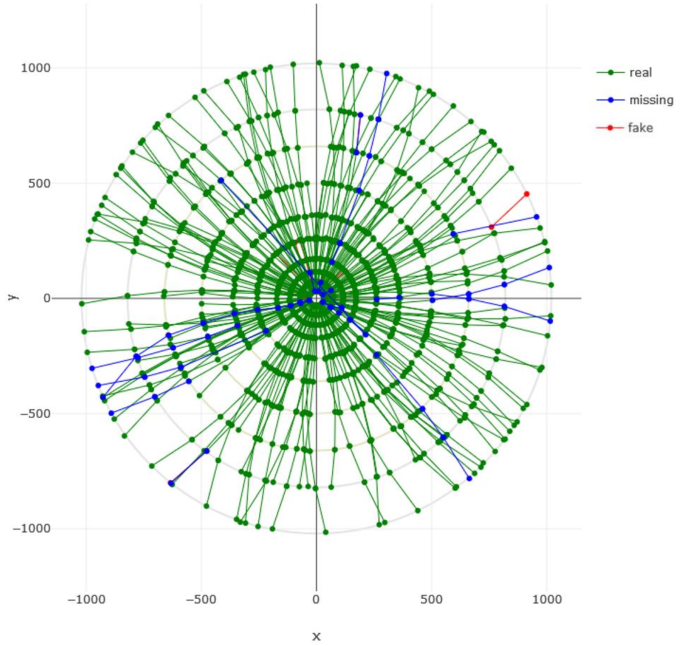
$$\text{Purity} = \frac{TP}{TP+FP} = \frac{\#\text{ of matched reconstructed doublets}}{\#\text{ of all reconstructed doublets}},$$

- QAOA+sub-QUBO provides **compatible performance as previous quantum annealing studies.**
- **<u>No sign of degradation in the real hardware</u>**

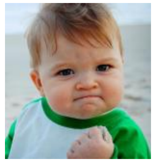
WIP: Triplet Efficiency & Purity







- **1st successful implementation of QAOA for tracking in the world!**
- **1st application of theoretically robust sub-QUBO method in HEP!**
- **1st usage of Chinese quantum computer for tracking! 自力更生!**

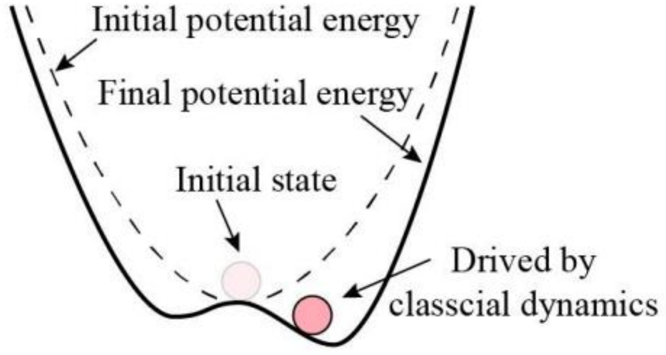


NEW!

CC Approach
(经典数据+计算, 量子启发算法)

H. Okawa, Q.-G. Zeng, X.-Z. Tao, M.-H. Yung, arXiv:2402.14718 (2024)

Simulated Bifurcation 量子启发算法



Quantum inspired algorithm

- Quantum annealing reaches the minimum energy through adiabatic theorem
- “Quantum-inspired” algorithms search for minimum energy through the **classical time evolution of differential equations**.
- **SB in particular can run in parallel unlike simulated annealing**, in which one needs to access the full set of spins & not suitable for parallel processing

Simulated Bifurcation (SB)

➤ **adiabatic Simulated Bifurcation (aSB)**

$$\dot{x}_i = \frac{\partial H_{\mathrm{SB}}}{\partial y_i} = \Delta y_i, \qquad \dot{y}_i = \frac{\partial H_{\mathrm{SB}}}{\partial x_i} = -[\boxed{K x_i^2} - p(t) + \Delta] x_i + \xi_0 \sum_{j=1}^{N} J_{ij} x_j$$

➤ **ballistic Simulated Bifurcation (bSB)**

$$\dot{x}_i = \frac{\partial H_{\mathrm{SB}}}{\partial y_i} = \Delta y_i, \qquad \dot{y}_i = \frac{\partial H_{\mathrm{SB}}}{\partial x_i} = (p(t) - \Delta) x_i + \xi_0 \sum_{j=1}^{N} J_{ij} x_j$$

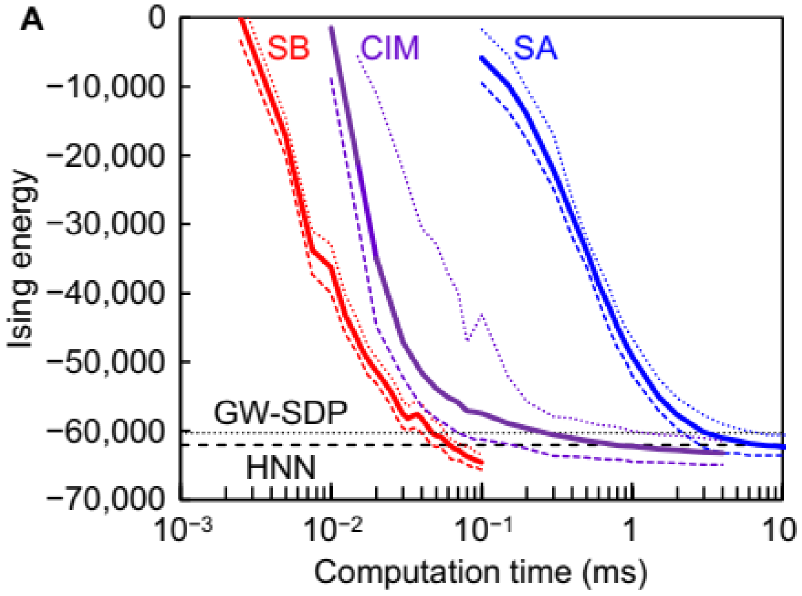
➤ **discrete Simulated Bifurcation (dSB)**

$$\dot{x}_i = \frac{\partial H_{\mathrm{SB}}}{\partial y_i} = \Delta y_i, \qquad \dot{y}_i = \frac{\partial H_{\mathrm{SB}}}{\partial x_i} = (p(t) - \Delta) x_i + \xi_0 \sum_{j=1}^{N} \boxed{J_{ij} \mathrm{sign}(x_j)}$$

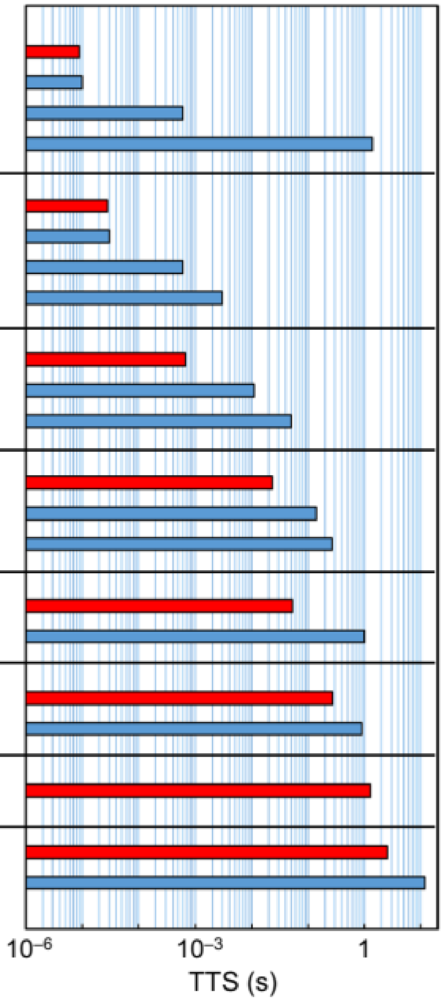
M.H. Yung

Simulated Bifurcation

Goto et al., Sci. Adv. 2019; 5 : eaav2372

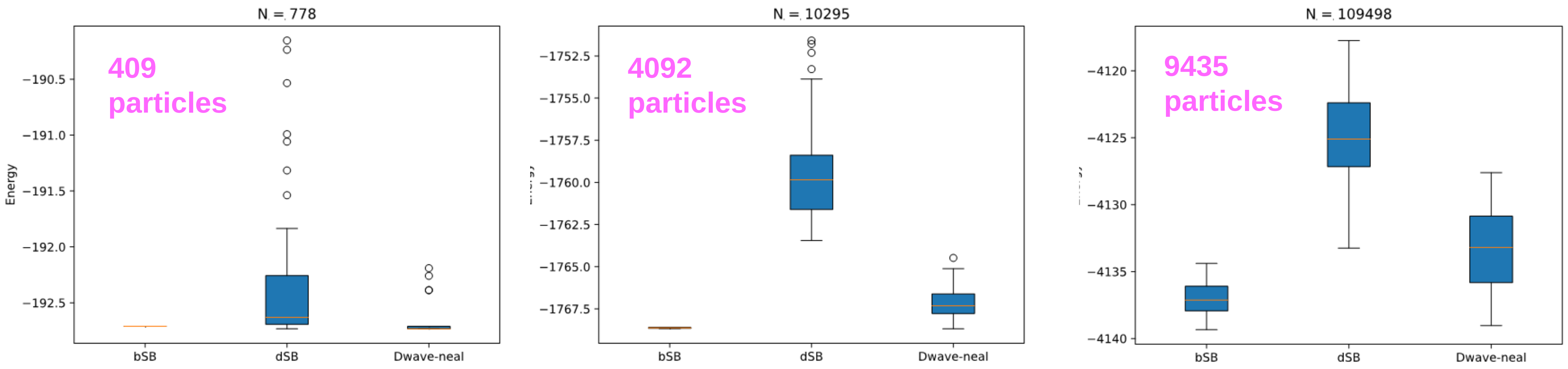


N	Connectivity	$J_{i,j}$	Machine	TTS
60	All-to-all	{±1}	**dSBM** RBM CIM QA	**9.2 μs** 10 μs 0.6 ms 1.4 s
100	All-to-all	{±1}	**dSBM** RBM SimCIM CIM	**29 μs** 30 μs 0.6 ms 3.0 ms
200	Sparse (Degree 3)	{0, −1}	**dSBM** QA CIM	**0.70 ms** 11 ms 51 ms
700	All-to-all	{±1}	**dSBM** SimCIM DA	**25 ms** 0.14 s 0.27 s
1024	All-to-all	{±1}	**dSBM** DA	**55 ms** 1 s
1024	All-to-all	16 bits {$-2^{15}+1, \ldots, 2^{15}-1$}	**dSBM** DA	**0.29 s** 0.9 s
2000 (K_{2000})	All-to-all	{±1}	**dSBM**	**1.3 s**
2000 (G22)	Sparse (1%)	{0, −1}	**dSBM** SimCIM	**2.7 s** 12 s



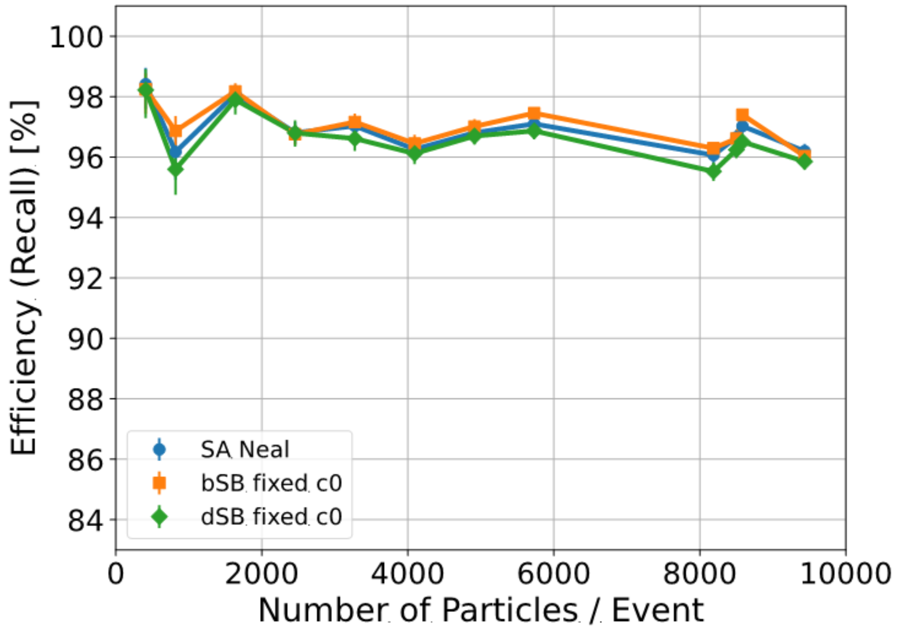
- **Simulated bifurcation is known to outperform other CC algorithms as well as quantum annealing for some problems**
- Simulated Coherent Ising Machine (CIM) had largely degraded performance in our study, so is not presented.

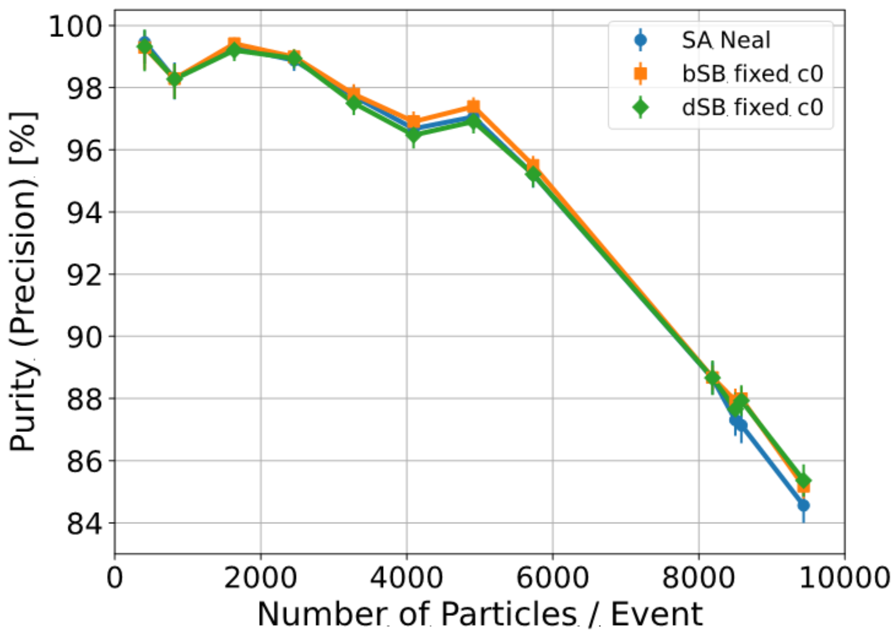
Mimimum Ising Energy Prediction



- Originally proposed adiabatic simulated bifurcation (aSB) is largely outperformed by new versions, so not shown here.
- **Ballistic simulated bifurcation (bSB) provides the best prediction of minimum energy with the least fluctuation**.
- Discrete simulated bifurcation (dSB) is not as good as the other two, but the impact on the reconstruction performance is not significant (next slide)

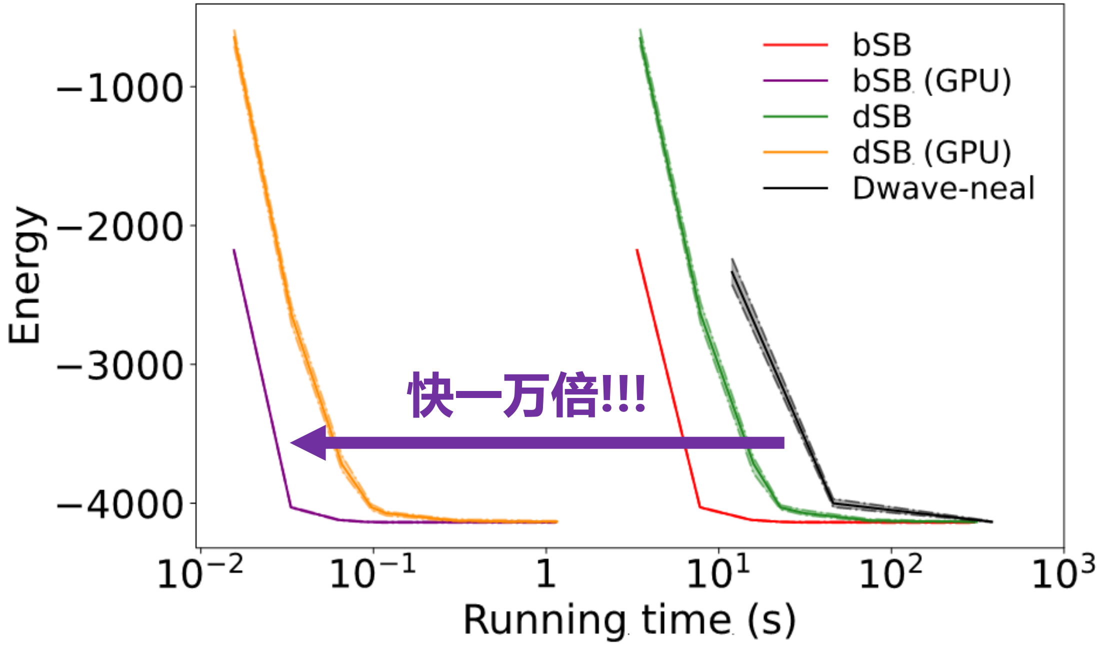
Track Efficiency & Purity w/ QAIA





- Simulated bifurcation provides **compatible or slightly better performance than D-Wave Neal.**
- **Track efficiency stays over 95%** for all dataset up to the highest HL-LHC conditions
- Purity degrades with track multiplicity but **>90% for <6000 particles, >84% even for ~10000 particles**.

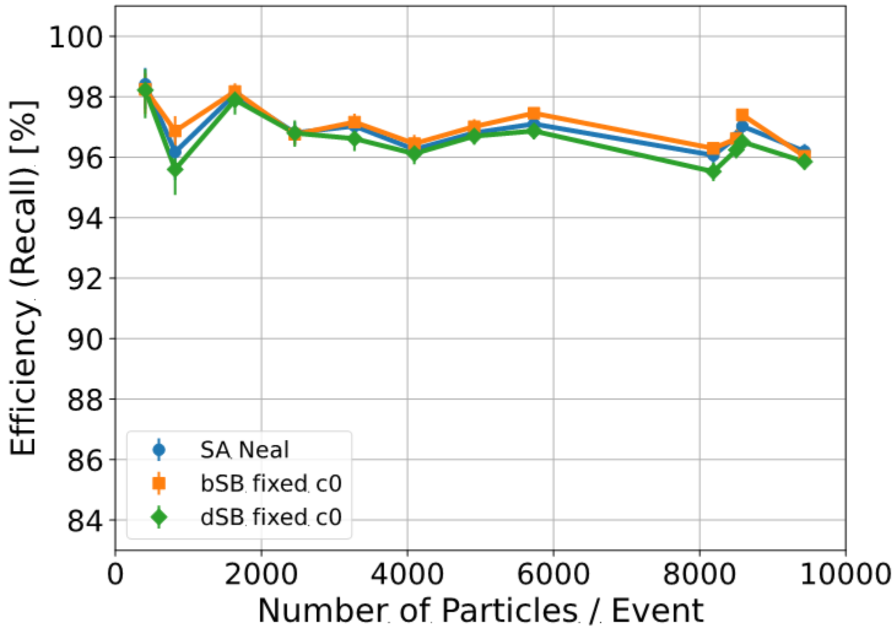
Computation Speed

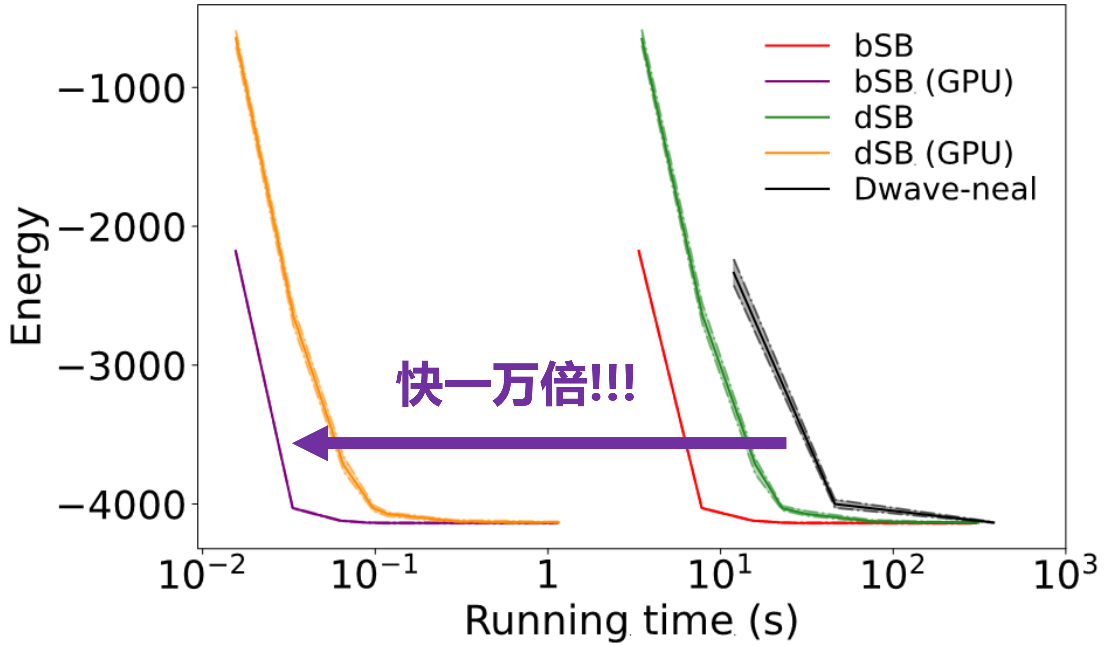


Data Information		Time to target [s]				
# of particles	QUBO size	bSB	bSB (GPU)	dSB	dSB (GPU)	D-Wave Neal
409	778	0.007	0.021	0.032	0.092	0.060
818	1431	0.012	0.019	0.293	0.478	0.169
1637	2904	0.012	0.019	0.293	0.478	0.169
2456	4675	0.014	0.017	–	–	0.479
3274	6945	0.032	0.022	–	–	1.229
4092	10295	0.005	0.022	0.015	0.065	0.030
4912	14855	0.027	0.016	–	–	2.165
5730	22022	0.109	0.042	–	–	3.853
8187	67570	0.488	0.028	–	–	404.297
8500	78812	1.899	0.108	–	–	785.732
8583	80113	1.321	0.067	–	–	93.782
9435	109498	3.884	0.140	–	–	1366.808

- Ballistic simulated bifurcation provides **4 orders of magnitude speed-up (1367s → 0.14s)** at most, compared to D-Wave Neal. → More speed-up expected with larger data size.
- Unlike D-Wave Neal, **simulated bifurcation can effectively run w/ multiple processing & GPU → Perfect match with HEP computing environment!!**

Simulated Bifurcation for Tracking



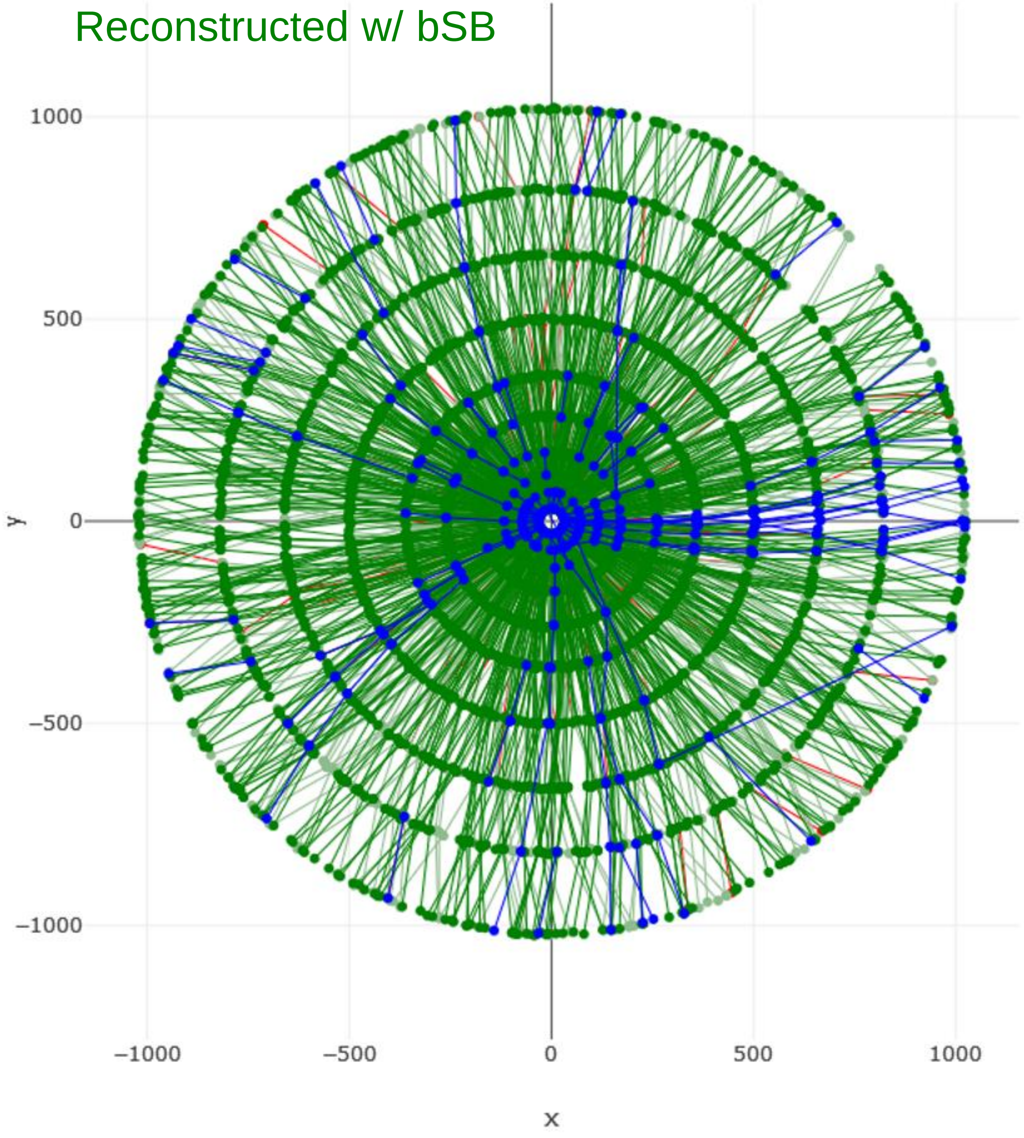


- **World's 1st implementation of simulated bifurcation in HEP!**
- **This quantum-inspired algorithm runs on classical computers & provides a practical solution which can be considered <u>NOW</u>.**

Summary

- Tracking is the highest CPU-consuming reconstruction task in the HL-LHC era.
- Improvement of existing methods & classical ML methods are bringing in improvement, but another leap from quantum machine learning would be highly exciting.
- Presented recent results on the quantum tracking using two complementary approaches: CQ approach (QAOA+subQUBO) & CC approach (quantum-annealing inspired algorithms).
- CQ approach: Promising tracking performance from the real quantum hardware.
- CC approach: Quantum-annealing inspired algorithms provide **four orders of magnitude speed-up** at most (& more speed-up expected w/ larger dataset) & **can already be considered for implementation**.
- Further studies are ongoing. Stay tuned!

Reconstructed w/ bSB



Thank you for listening!

感谢聆听！

Backup

Quantum Clouds

From 王正安's slides
(&中国信通院's material)

量子云平台竞相推出，用户生态处于培育阶段

CAICT 中国信通院

➤ **量子计算云平台为用户提供量子计算机或模拟器远程访问，处于应用生态构建培育阶段，根据供应侧服务模式可分为含硬件云平台和纯软件云平台两种。**

硬件类型	超导			离子阱	光量子	半导体/超导	退火	云平台服务供应		
供应商	IBM	rigetti	Google	IONQ	XANADU	QuTech	D:Wave	aws		STRANGE WORKS
平台名称	IBM Quantum	Quantum Cloud Services (QCS)	Google Cloud	IonQ Quantum Cloud	Xanadu Quantum Cloud	Quantum Inspire	Leap	Amazon Braket	Azure Quantum	strangeworks QC
最新处理器	Osprey	Aspen-M-2	Sycamore	Forte	Borealis	Spin-2 Starmon-5	Advantage	D-Wave、IonQ、OQC、Rigetti、QuEra、Xanadu	IonQ、QCI Rigetti、Quantinuum、Pasqal	IBM、Xanadu、Quantinuum、Rigetti、......
量子比特数	433	80	72	32	216	2；5	5000+	QPU family	QPU family	QPU family

硬件类型	超　导				超导/离子阱	中性原子	模拟器		云平台服务
单位名称	北京量子院&中科院物理所	中科院量子创新研究院&阿里&济南量子技术研究院&国盾量子	本源量子	浙江大学	百度	武汉量子技术研究院	华为	阿里	弧光量子
平台名称	quafu	"量子计算云平台"	本源量子云	太元一号	量易伏	酷原量子云 (据报道年底发布)	HiQ	太章	弧光量子云平台
量子比特数	45；18；10	12	6	10	8；10；1	100+ (据报道)	——	——	——

国内量子云平台起步较晚，样机比特数较少、用户数量较少且不稳定、免费使用（国外已形成收费模式），尚未形成良好的生态模式。
未来发展关注点：**1.**提升硬件性能；**2.**深化应用探索；**3.**探索合作与商用模式。

9

← **some numbers outdated (rapid development!!)**

$$QUBO = \sum_i a_i x_i + \sum_{i>j} b_{ij} x_i x_j$$

Multiple Solution Instances

- 3 parameters (N_I, N_E, N_S) in this sub-QUBO method.
- Extract N_I quasi-optimal solutions from full-QUBO classically.
- Randomly select N_S solution instances from N_I.
- Focus on particular binary variable x_i. Rank them in accordance to how much they vary over N_S solution instances. Highly varying x_i will be included in the sub-QUBO model.
- Pick-up process of N_S solution from quantum computing is repeated N_E times & N_E sub-QUBO models are considered.
- Returns a pool of N_I solutions & the best solution will be chosen.

Y. Atobe, M. Tawada, N. Togawa, IEEE Trans. Comp. 71, 10 (2022) 2606