



量子信息导论

PHYS5251P

中国科学技术大学
物理学院/合肥微尺度物质科学国家研究中心

陈凯

2026.9

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◆ 助教 程雷雨, cly138@mail.ustc.edu.cn

参考书目

教材

- ◆ Quantum computation and quantum information by M.A. Nielsen and I.L. Chuang, Cambridge University Press, 2010

其他参考书

◆ 量子信息

马雄峰、张行健、黄溢智，《量子信息简明教程》，清华大学出版社，2023.

◆ 量子力学

王向斌、沈艺鑫、于云龙、秦季茜、徐海，《量子力学基础教程》，清华大学出版社，2023.

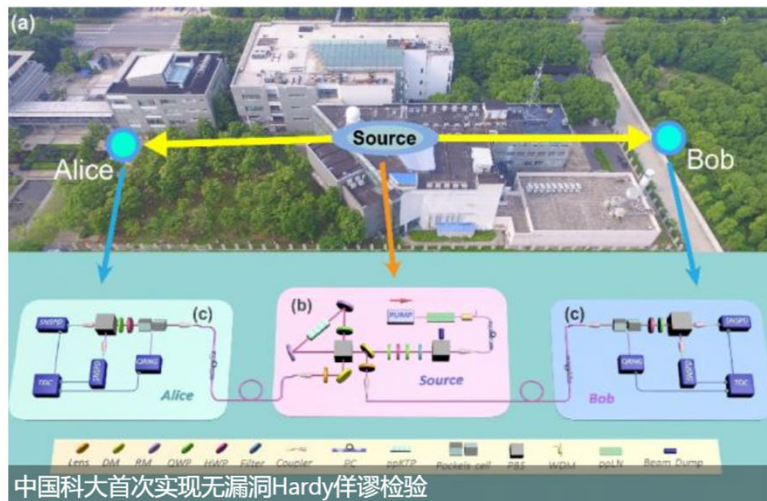
Course Description

This course is open to all graduate students and undergraduates. The final grades are based on:

- ◆ final exam (60%),
- ◆ homework and attendance of the class (20%),
- ◆ a report about quantum information (20%, the subject can be arbitrary, which is preferably related to your current research project, recent progress or your own ideas along one specific area on theoretical or experimental quantum information)

量子物理与量子信息研究部

Explore quantum mystery, enable quantum applications!

[首页](#)[研究方向](#)[量子卫星](#)[团队成员](#)[新闻动态](#)[研究进展](#)[学术报告](#)[论文发表](#)[公告通知](#)[招生信息](#)[相关链接](#)

关于我们

量子物理与量子信息研究部成立于2001年，研究部主任为潘建伟院士。研究领域为量子光学与量子信息，研究方向包括量子力学基本原理检验、光纤量子通信、自由空间量子通信、量子存储与量子中继、光学量子计算、超导量子计算、超冷原子量子模拟、量子精密测量以及相关理论研究等。我们已经搭建了众多相关实验平台，建立和发展了一整套与量子信息实验研究相关的分析探测设备和手段，研究条件具有国际先进水平。

[阅读更多](#)

新闻动态

- 2026-01-26 ‘祖冲之三号’入选2025年度中国十大科技进展新闻
- 2025-12-26 “祖冲之三号”量子计算成果入选两项年度科技新闻榜单
- 2025-12-06 中国科大潘建伟教授获2025腾冲科学大奖
- 2025-11-27 我校苑震生教授获第三期腾讯“新基石研究员项目”资助
- 2025-11-27 第一届物质科学青年学者学术交流研讨会在合肥召开
- 2025-11-21 中国科大彭承志当选中国科学院院士
- 2025-10-28 中国科大王辉教授获2025年可持续发展青年科学家奖

研究进展

- 2026-06-22 中国科大实现基于量子存储的长基线光学干涉仪
- 2026-05-13 中国科大成功研制“九章四号”量子计算原型机
- 2026-03-06 中国科大实现稳定性和不确定度均达到 10^{-19} 量级的光钟
- 2026-02-06 中国科大构建可扩展量子中继的基本模块，实现量子网络研究的重大突破
- 2025-12-22 中国科大在量子纠错领域达到关键里程碑
- 2025-11-28 中国科大利用超导量子处理器首次在量子体系中实现并探测高阶非平衡拓...
- 2025-09-05 中国科大在量子模拟实验中观测到“弦断裂”现象

学术报告

- 2026-08-27 Exploring Fermionic Quantum Matter at the Single-Atom Level
- 2026-08-19 人工智能时代的数学研究
- 2026-07-24 Device Fabrication and Relative Physics in Novel Quantum Materials system
- 2026-07-23 Photoacoustic, Light-Speed, and Quantum Imaging/Physics
- 2026-07-06 Quantum Computing with Oscillators and Qubits
- 2026-06-26 Exotic Quantum Statistics in 1D Bose Gases
- 2026-06-12 Raising Schrödinger's kittens

中国科学院量子信息与量子科技创新研究院 CAS CENTER FOR EXCELLENCE IN QUANTUM INFORMATION AND QUANTUM PHYSICS

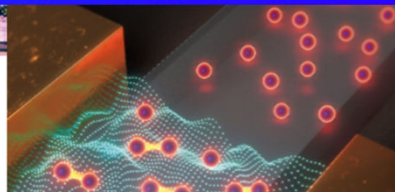
首页 研究院概况 科研体系 科研成果 科研队伍 人才招聘 新闻公告 前沿动态 党群建设

搜索

中国科大首次实现真空涨落对超导的增强效应

2026-08-19

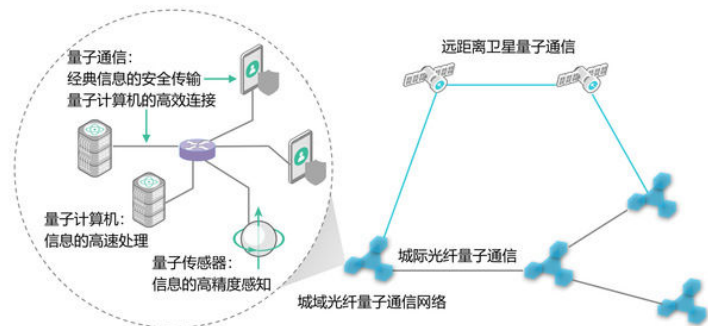
近日，中国科学技术大学曹长涛教授、程广辉教授领衔的研究团队，联合上海交通大学蒋庆东教授以及麻省理工学院Frank Wilczek教授（2004年诺贝尔物理学奖得主）等合作者，在量子态调控领域取得重要进展，首次利用唯像实现了真空涨落增强超导（图a）。如何将微弱的真空涨落转化为调控宏观量子态的...



中国科大构建可扩展量子中继的基本模块，实现量子网络研究的重大突破

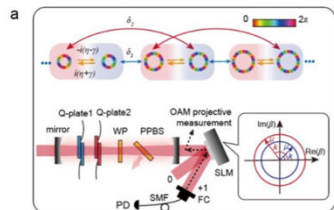
2026-02-06

近日，中国科学技术大学潘建伟及其同事在可扩展量子网络研究方面取得重大突破。汪野、万雍、张强、潘建伟等与济南量子技术研究院、中国科学院上海微系统与信息技术研究所、香港大学、清华大学等的研究人员合作，构建出可扩展量子中继的基本模块，使得远距离量子网络成为现实可能。与此同时，包小辉...



新闻动态

更多



中国科大直接观测复动量空间中的非厄米能谱形变

2026-08-14

中国科大郭光灿院士团队在非布洛赫能带与非厄米物理量子模拟研究中取得重要进展。该团队李传烽、许金时、易为、杨木等人，基于简并光学谐振腔中的光子轨道

中国科大首次实现真空涨落对超导的增强效应 08-19

中国科大直接观测复动量空间中的非厄米能谱... 08-14

中国科大将量子存储器间纠缠距离提升至420... 08-12

潘建伟教授获第三届联合国教科文组织 - 门... 07-12

中国科大实现远距离芯片化量子通信网络 06-22

中国科大实现基于量子存储的长基线光学干... 06-22

中国科大实现碳化硅氧-空位色心的高效制备... 05-20

中国科大成功研制“九章四号”量子计算原... 05-13

中国科大建立星汉二号多模式量子中继并实... 05-09

中国科大实现二色量子网络非局域性实验 05-08

通知公告

更多

◆合肥国家实验室技术支撑岗位招聘启事... 07-29

◆合肥国家实验室技术支撑人员招聘启事 07-13

◆合肥国家实验室管理岗位招聘启事 07-09

◆合肥国家实验室技术支撑岗位招聘启事 06-30

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学术报告

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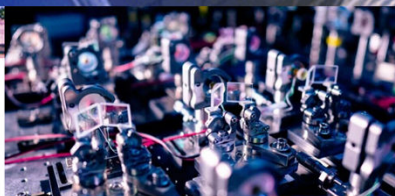
◆【2025-12-24】智能时代下异质集成材料与器件... 12-24

◆【2025-11-28】Quantum optics with radiati... 11-28

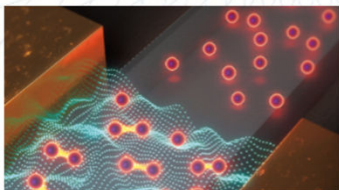
中国科大成功研制“九章四号”量子计算原型机

2026-05-13

中国科学技术大学潘建伟、陆朝阳、张强、刘乃乐等，联合济南量子技术研究院、山东大学、清华大学、上海人工智能实验室、崂山实验室、国家并行计算机工程技术研究中心等单位，成功研制出1024个量子压缩态输入8176模式的可编程量子计算原型机“九章四号”，首次模拟和探测高达3050个光子的量子态。 “...



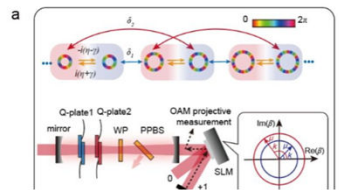
新闻动态



中国科大首次实现真空涨落对超导的增强效应

2026-08-19

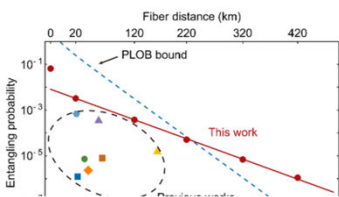
近日,中国科学技术大学曾长途教授、程广晖教授领衔的研究团队,联合上海交通大学蒋庆东教授以及麻省理工学院Frank Wilczek教授(2004年诺贝尔物理学奖得主)等合作者,在量子物态调控领域取得重要进展,首次利...



中国科大直接观测复动量空间中的非厄米能谱形变

2026-08-14

中国科大郭光灿院士团队在非布洛赫能带与非厄米物理量子模拟研究中取得重要进展。该团队李传锋、许金时、易为、杨木等人,基于简并光学谐振腔中的光子轨道角动量(OAM)合成维度,发展了复动量分辨谱探测方法,...



中国科大将量子存储器间纠缠距离提升至420公里

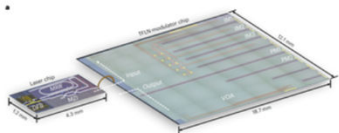
2026-08-12

近日,中国科学技术大学潘建伟、包小辉、张强等与济南量子技术研究院、中国科学院上海微系统与信息技术研究所等单位的研究人员合作,在远距离量子中继研究中取得重要突破,成功实现了两个冷原子量子存储器间跨越...

潘建伟教授获第三届联合国教科文组织 - 门捷列夫国际基础科学奖

2026-07-12

7月10日,联合国教科文组织(UNESCO)正式宣布,中国科学院院士、中国科学技术大学教授潘建伟因“在大尺度安全量子通信和可扩展量子计算方面的开创性贡献”(for his seminal contributions to large-scale secure...



中国科大实现远距离芯片化量子通信网络

2026-06-22

近日,中国科大潘建伟、徐飞虎等与中山大学、上海交通大学等单位的科研人员合作,通过发展氮化硅与薄膜铌酸锂混合集成光子学芯片,实现了基于双场量子密钥分发(TF-QKD)协议的芯片化量子通信网络,在最远540公...

前沿动态

欧盟跨境量子通信网络项目QUANT-GPICz正式启动

2026-06-03

IBM计划五年内投入超百亿美元加码量子计算

2026-05-28

美国国家科学基金会启动15亿美元“NSF X-Labs”计划 首轮资助聚焦量子系统与新一代科学仪器

2026-05-14

德国、瑞士两国学者实现光晶格中费米原子高保真度量子门

2026-04-13

英国成功发射SPOQC卫星用于量子安全通信

2026-03-31

英国宣布20亿英镑量子技术投资计划

2026-03-17

美国学者通过hBN实现对超导体的腔QED调控

2026-03-09

美国学者演示纠缠辅助的量子增强长基线望远镜

2026-03-04

我国学者实现核钟关键真空紫外连续激光光源

2026-02-24

美国学者实现并行单原子-腔强耦合,开启“多腔量子电动力学”新范式

2026-02-13

澳大利亚学者实现大规模硅基原子量子点阵列量子模拟

2026-02-09

基于纠缠原子团阵列的多参数量子传感的首次实验演示

2026-01-30

探索量子与经典的边界:奥地利学者首次观测到7000个原子的量子干涉

2026-01-29

美国学者利用全息超表面构建360000光镊阵列

2026-01-16

媒体关注	更多	科研体系	更多	快速导航	
【中国科学报】研究实现量子存储器间跨越420公里...					
【科技日报】量子存储器间纠缠距离提升至420公里		量子通信研究部		量子计算研究部	
【新华每日电讯】中国科学家首获门捷列夫国际基础...					
【合肥晚报】潘建伟获一项国际大奖 成为首位获得...				科研队伍	人才招聘
【人民日报】基础研究点亮未来之光					
【科学网】潘建伟获门捷列夫国际基础科学奖		量子精密测量研究部		工程技术支撑部	
					
				党群建设	联系我们

量子卫星成功发射

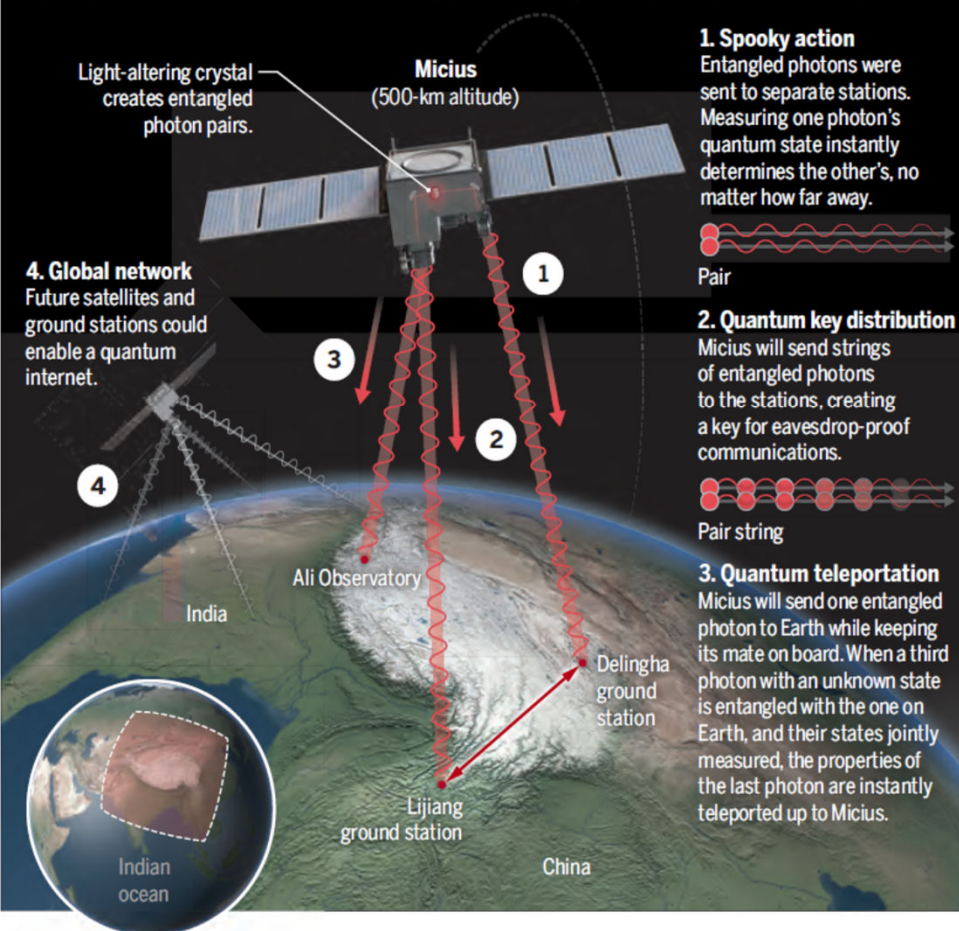


2016年8月16日1时40分，我国在酒泉卫星发射中心用长征二号丁运载火箭成功将世界首颗量子科学实验卫星发射升空。

Satellite-based entanglement distribution over 1200 kilometers

Quantum leaps

China's Micius satellite, launched in August 2016, has now validated across a record 1200 kilometers the "spooky action" that Albert Einstein abhorred (1). The team is planning other quantum tricks (2–4).



Retired research chimps
stuck in limbo p. 1114

Job losses undermine
educational advancement p. 1127

Marine predators shape
prey defenses p. 1178

Science

\$15
16 JUNE 2017
sciencemag.org

AAAS

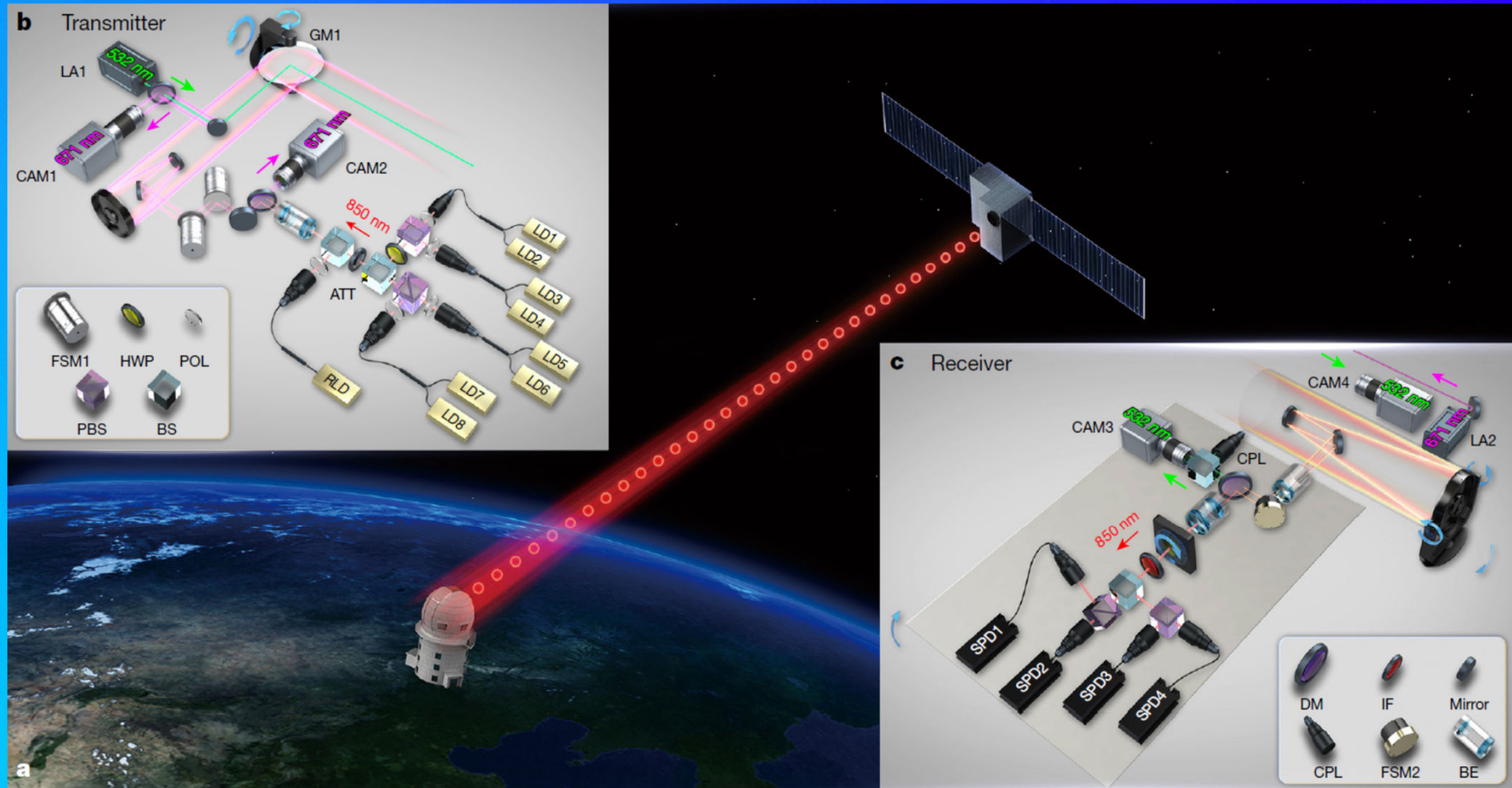


QUANTUM REACH

Entangled photon pairs sent
from space to Earth
pp. 1110 & 1140

J. Yin *et al.*, **Science** 356 (2017) 1140–1144

Satellite-to-ground quantum key distribution

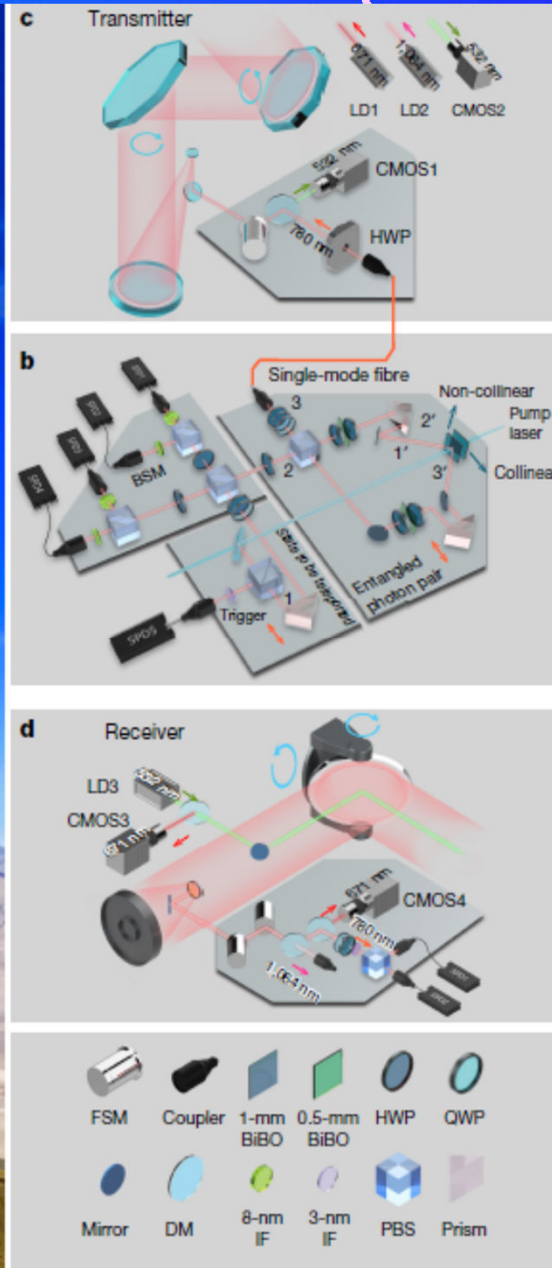


Satellite-to-ground quantum key distribution. *Nature*

<http://dx.doi.org/10.1038/nature23655>

S.-K. Liao *et al.*, **Nature** 549 (2017) 43–47

Ground-to-satellite quantum teleportation



Ground-to-satellite quantum teleportation. *Nature*
<http://dx.doi.org/10.1038/nature23675> (2017).

J.-G. Ren *et al.*, **Nature** 549
 (2017) 70–73

“墨子号”实现基于纠缠的无中继千公里量子保密通信



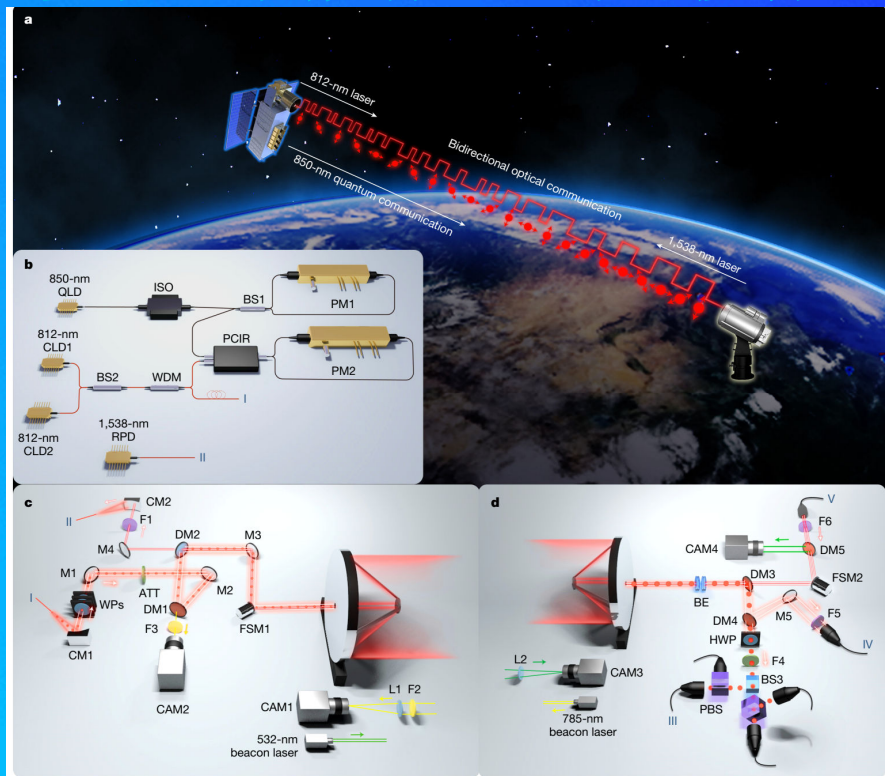
J. Yin *et al.*, **Nature** 582 (2020) 501-505

世界首颗量子微纳卫星成功发射



2022年7月27日，世界首颗量子微纳卫星在酒泉卫星发射中心搭载“力箭一号”运载火箭成功发射。该卫星的科学目标是在世界上首次实现基于微纳卫星和小型化地面站之间的实时星地量子密钥分发，为构建低成本、实用化的天地一体化广域量子保密通信网络奠定基础。

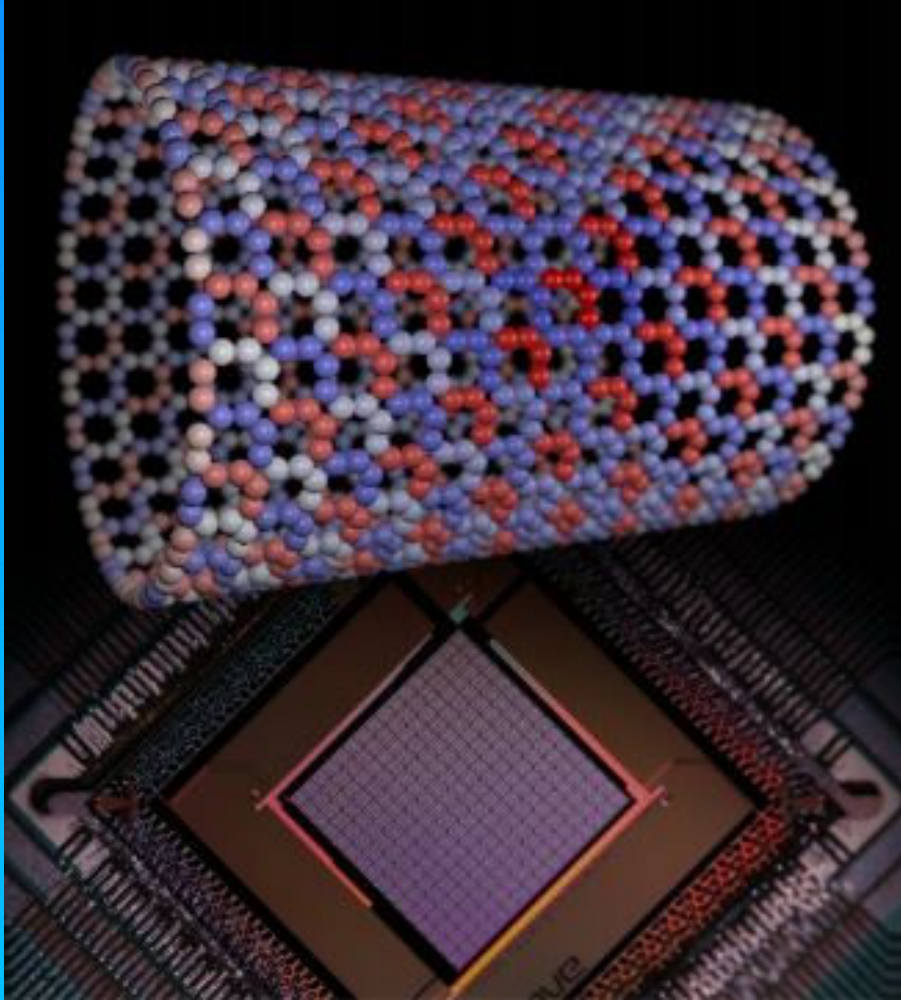
实现量子微纳卫星与可移动地面站间的实时星地量子密钥分发



中国-南非“一次一密”加密传输的图片（上图：长城照片；下图：南非斯图滕布什大学实验现场）

中国科学技术大学潘建伟、彭承志、廖胜凯等，联合济南量子技术研究院、中国科学院上海技术物理研究所、微小卫星创新研究院等单位组成的研究团队，在国际上首次实现量子微纳卫星与小型化、可移动地面站之间的实时星地量子密钥分发，在单次卫星通过期间实现了多达1百万比特的安全密钥共享。在此基础上，联合团队和南非斯图滕布什（Stellenbosch）大学科研团队合作，在中国和南非之间相隔12900多公里的距离上建立了量子密钥，完成对图像数据“一次一密”加密和传输。该工作为实用化卫星量子通信组网铺平了道路。

Quantum simulation



Programmable simulation of
quantum magnets

Observation of topological phenomena in a programmable lattice of 1,800 qubits
<https://doi.org/10.1038/s41586-018-0410-x>

A.D. King *et al.*, **Nature** 560 (2018) 456-460

量子模拟

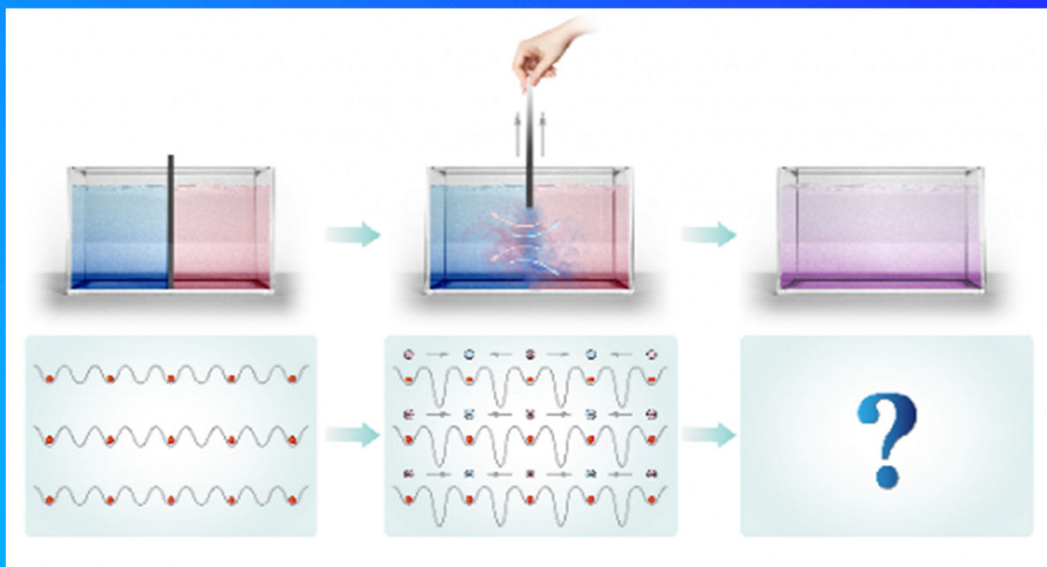
ULTRACOLD ATOMS IN OPTICAL LATTICES

在超冷原子光晶格
中实现大规模高保
真度量子纠缠对的
同步制备

获得了纠缠保真度
为**99.3%**的**1250对**
纠缠原子!

B. Yang *et al.*, **Science** 369 (2021) 550-553

量子模拟



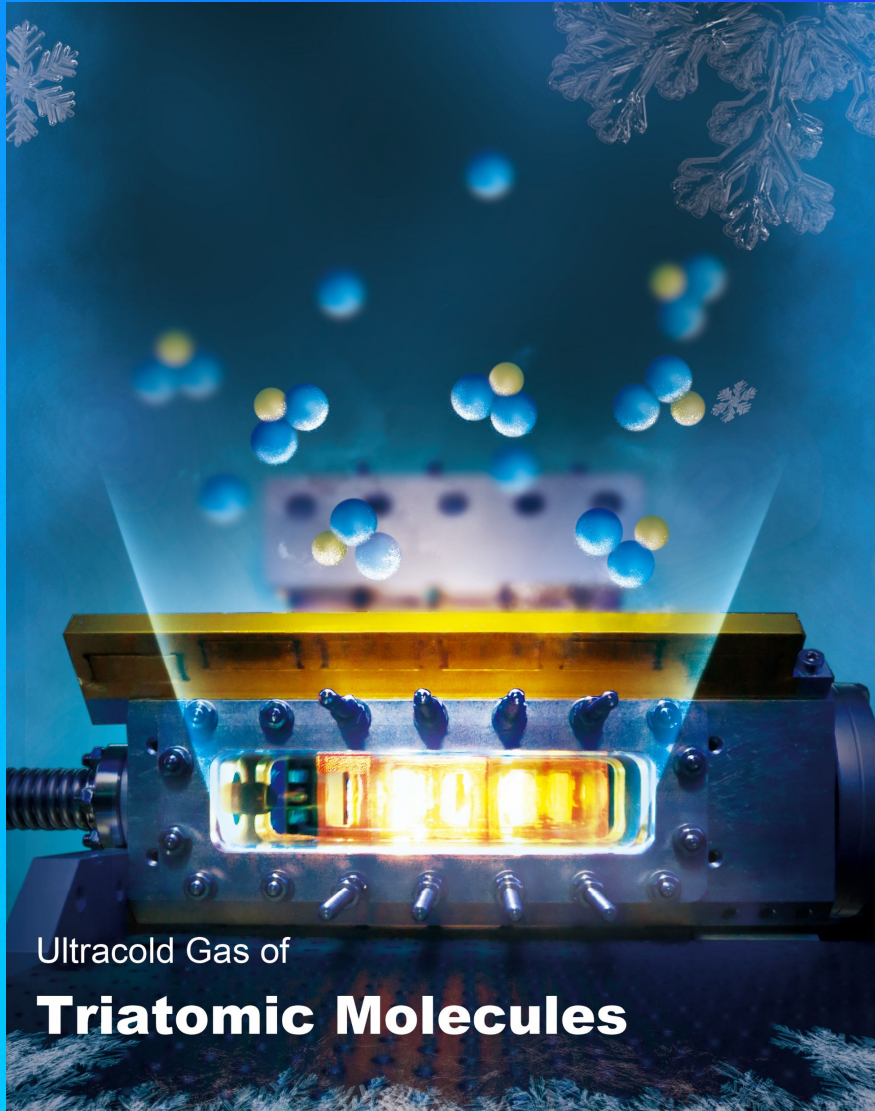
从非平衡态过渡到平衡态的热化动力学示意图。上图：经典图像类比。容器左、右半部分装有温度不同的水，当快速抽离中间隔板时，系统处于非平衡态，经过两个子系统中水分子的交换和碰撞，最终达到热平衡。下图：本工作研究的物理问题。束缚在光晶格中的原子被制备到满足特定规范对称性的量子多体初态，通过调控实验参数快速改变原子之间的相互作用，把系统置于一个非平衡态，该强关联量子多体系统能否通过特定的热化机制达到平衡态？

（制图：陈磊，周肇宇，梁琰，苑震生）

首次实验研究了规范对称性约束对量子多体系统热化动力学的影响，并且观测到具有相同守恒量的不同初态热化到同一个平衡态的过程，验证了热化过程造成的量子多体系统初态信息的“丢失”，建立了规范场理论早期非平衡动力学与最终热平衡态之间的联系，在使用规模化的量子模拟器求解复杂物理问题的道路上取得了重要进展。

Z.-Y. Zhou *et al.*, **Science** 377 (2022) 311–314

量子模拟



Creation of an ultracold gas of triatomic molecules from an atom-diatom molecule mixture

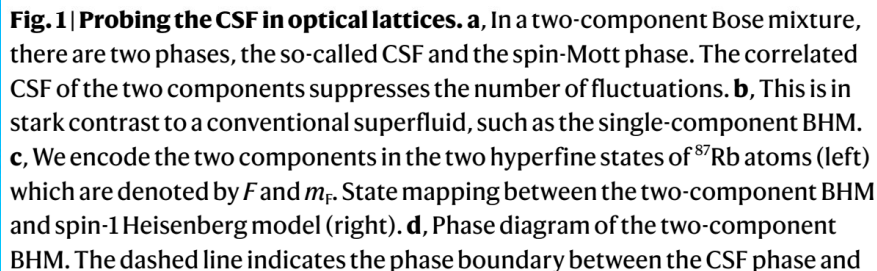
利用相干合成方法在国际上首次制备了高相空间密度的超冷三原子分子系综。研究团队基态双原子分子和原Feshbach共振附近利用磁缔合技术从简并的钠钾分子-钾原子混合气中制备了超冷三原子分子系综，向基于超冷分子的超冷量子化学和量子模拟研究迈出了重要一步。

Ultracold Gas of

Triatomic Molecules

H. Yang, J. Cao, Z. Su, J. Rui, B. Zhao and J.-W. Pan
Science 378 (2022) 1009–1013

量子模拟



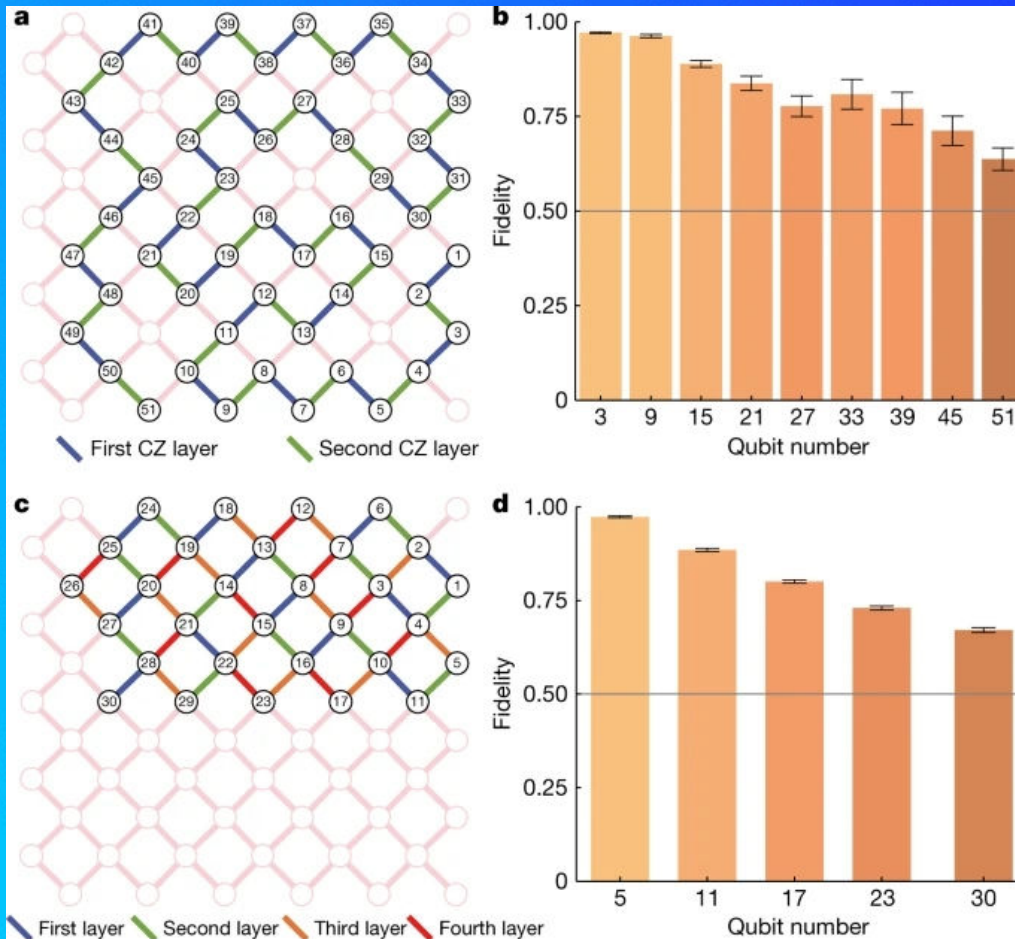
spin-Mott phase obtained from mean field theory. The solid arrow is the adiabatic passage to the CSF phase (yellow star) used in our experiments. **e**, Illustration of the experimental sequence. **i**, **ii**, State preparation of the doublon-occupied spin-Mott chains. **iii**, Adiabatic passage to the CSF phase. **iv**, Stern–Gerlach separation and doublon-splitter operations for spin- and number-resolved detection. **f**, A typical raw picture (right) of the $L = 6$ chain after Stern–Gerlach separation and doublon-splitter operations and the corresponding read-out in the two-component BHM and Heisenberg model (left).

潘建伟、苑震生、邓友金等与合作者在超冷原子量子模拟实验中，首次观测到对流超流相（**counterflow superfluidity**）这一新奇量子物态，证实了对流的双组分超流体共同形成绝缘体的特性。（**Nature Physics**）上。

量子计算

Generation of genuine entanglement up to 51 superconducting qubits

研究团队成功实现了**51**个超导量子比特簇态制备和验证，刷新了所有量子系统中真纠缠比特数目的世界纪录，并首次实现了基于测量的变分量子算法的演示。该工作将各个量子系统中真纠缠比特数目的纪录由原先的**24**个大幅突破至**51**个，充分展示了超导量子计算体系优异的可扩展性，对于多体量子纠缠研究、大规模量子算法实现以及基于测量的量子计算具有重要意义。



S.-R. Cao *et al.*, *Nature* 619 (2023) 738–742

量子计算

Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor

中国科学技术大学潘建伟、朱晓波、彭承志等，与上海量子科学研究中心、河南省量子信息与量子密码重点实验室、中国计量科学研究院、济南量子技术研究院、西安电子科技大学微电子学院以及中国科学院理论物理研究所等单位合作，成功构建了105比特（包含105个可读取比特和182个耦合比特）超导量子计算原型机“祖冲之三号”，实现了对“量子随机线路采样”任务的快速求解。与现有最优经典算法相比，“祖冲之三号”处理量子随机线路采样问题的速度比目前最快的超级计算机快15个数量级，超过谷歌2024年10月公开发表的最新成果6个数量级[Nature 634, 328 (2024)]。这一成果是我国继超导量子计算原型机“祖冲之二号”实现超导量子计算体系最强量子计算优越性 [PRL 127, 180501 (2021), Science Bulletin 67, 240 (2022)]后，再一次打破超导体量子计算优越性纪录。为《物理评论快报》3月3日封面论文。

D.X. Gao *et al.*,
Phys. Rev. Lett. 134, 090601, 2025

绪论

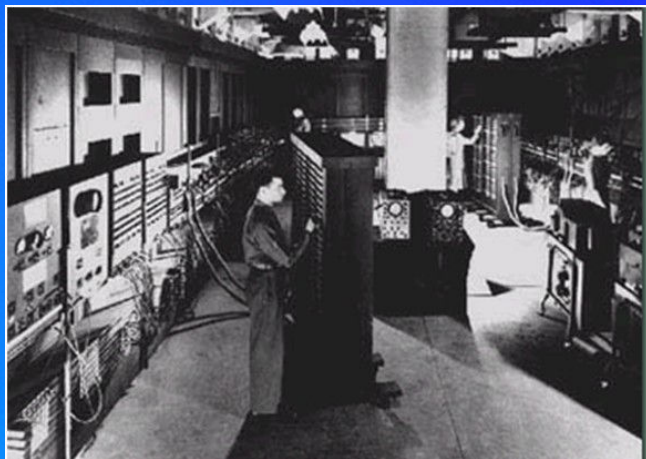
量子信息概念、历史和展望





冯·诺依曼

经典计算机和信息处理



第一代计算机



Roadrunner超级计算机



NASA太空高速互联网



联想笔记本



苹果笔记本



阿里云

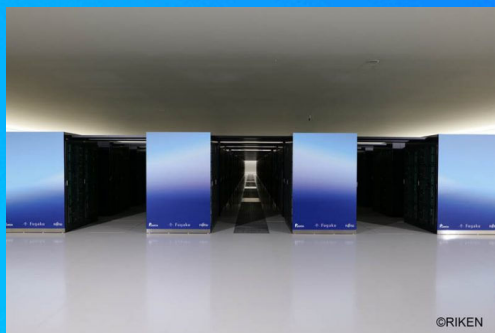
超级计算机



Frontier（美国）



Summit（美国）



Fugaku(富岳)



Sierra（美国）



Lumi（芬兰）



神威 太湖之光 中国

超级计算机

TOP10 System - November 2023

$R_{\max}$ and R_{peak} values are in PFlop/s.
For more details about other fields,
check the [TOP500 description](#).

R_{peak} values are calculated using the
advertised clock rate of the CPU. For
the efficiency of the systems you
should take into account the Turbo
CPU clock rate where it applies.

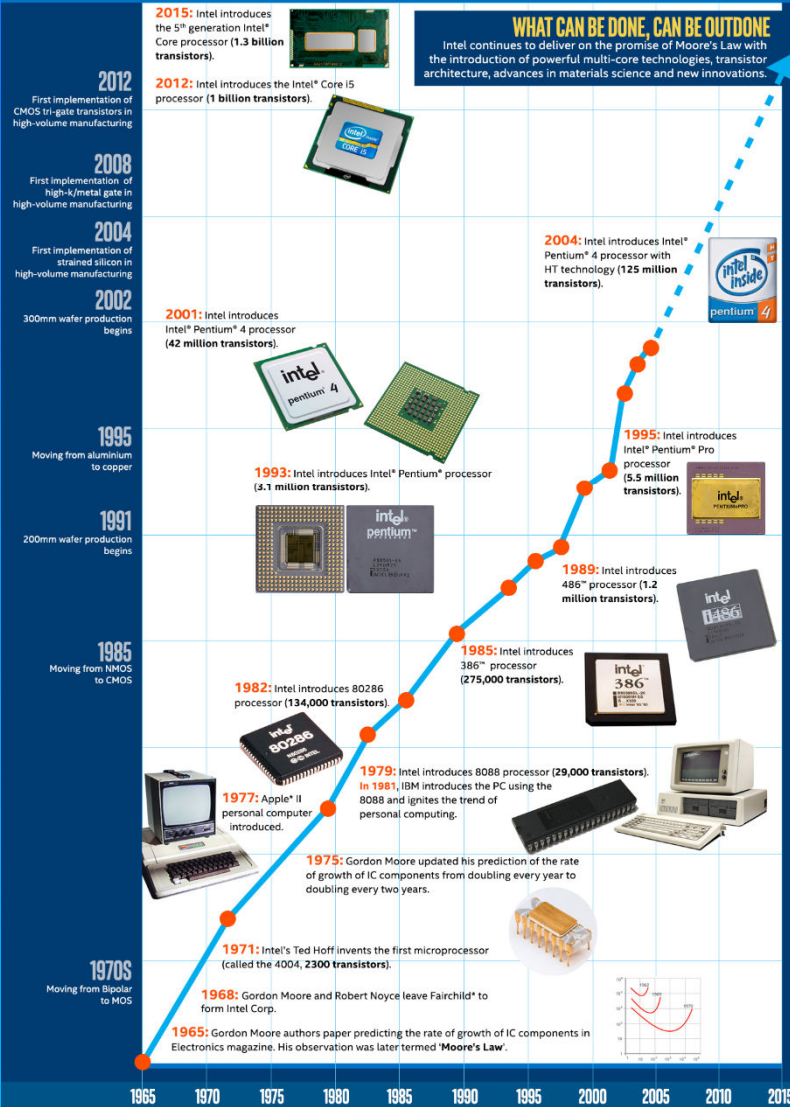
<https://www.top500.org/lists/top500/2023/11/>

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	8,699,904	1,194.00	1,679.82	22,703
2	Aurora - HPE Cray EX - Intel Exascale Compute Blade, Xeon CPU Max 9470 52C 2.4GHz, Intel Data Center GPU Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States	4,742,808	585.34	1,059.33	24,687
3	Eagle - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Microsoft Azure United States	1,123,200	561.20	846.84	
4	Supercomputer Fugaku - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442.01	537.21	29,899
5	LUMI - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE EuroHPC/CSC Finland	2,752,704	379.70	531.51	7,107
6	Leonardo - BullSequana XH2000, Xeon Platinum 8358 32C 2.6GHz, NVIDIA A100 SXM4 64 GB, Quad-rail NVIDIA HDR100 Infiniband, EVIDEN EuroHPC/CINECA Italy	1,824,768	238.70	304.47	7,404
7	Summit - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148.60	200.79	10,096
8	MareNostrum 5 ACC - BullSequana XH3000, Xeon Platinum 8460Y+ 40C 2.3GHz, NVIDIA H100 64GB, Infiniband NDR200, EVIDEN EuroHPC/BSC Spain	680,960	138.20	265.57	2,560
9	Eos NVIDIA DGX SuperPOD - NVIDIA DGX H100, Xeon Platinum 8480C 56C 3.8GHz, NVIDIA H100, Infiniband NDR400, Nvidia NVIDIA Corporation United States	485,888	121.40	188.65	
10	Sierra - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94.64	125.71	7,438



MOORE'S LAW TIMELINE

Moore's Law – the observation that computing dramatically decreases in cost at a regular pace – is short-hand for rapid technological change. Over the past 50 years, it has ushered in the dawn of the personalization of technology and enabled new experiences through the integration of technology into almost all aspects of our lives.



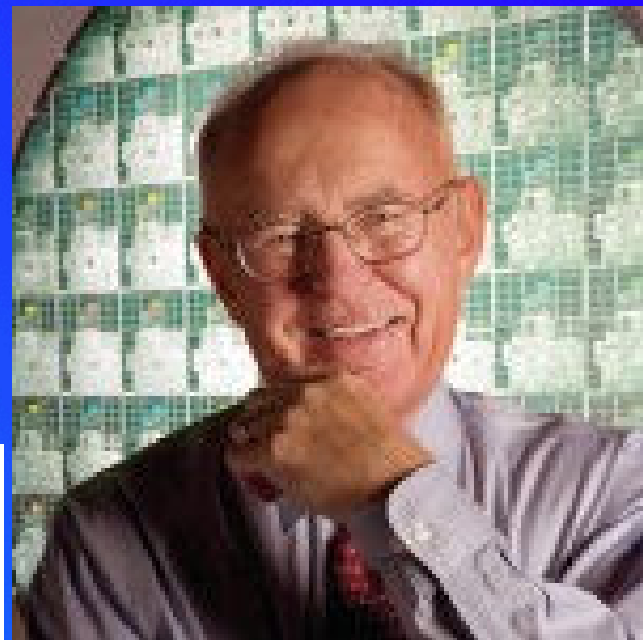
For more information, please visit intel.com.

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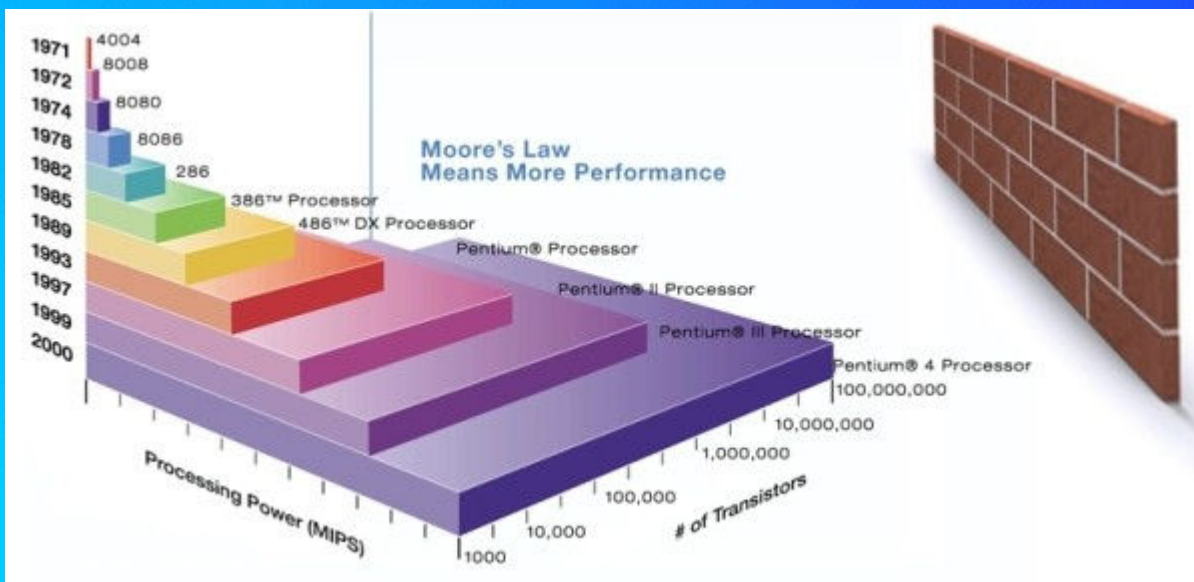


经典计算机和信息处理

“The number of transistors per chip
doubles within two years”
(Apr 19, 1965)



Gordon E. Moore,
Co-founder of Intel



1 The accelerating pace of change ...



2 ... and exponential growth in computing power ...

Computer technology, shown here climbing dramatically by powers of 10, is now progressing more each hour than it did in its entire first 90 years

COMPUTER RANKINGS

By calculations per second per \$1,000

Analytical engine
Never fully built, Charles Babbage's invention was designed to solve computational and logical problems



Colossus
The electronic computer, with 1,500 vacuum tubes, helped the British crack German codes during WW II



UNIVAC I
The first commercially marketed computer, used to tabulate the U.S. Census, occupied 943 cu. ft.



Apple II
At a price of \$1,298, the compact machine was one of the first massively popular personal computers

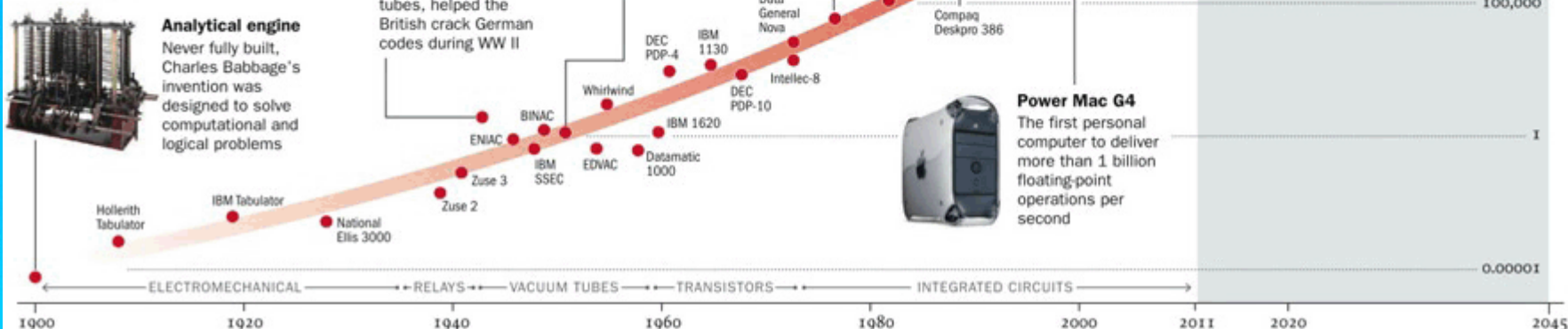
3 ... will lead to the Singularity

2045
Surpasses brainpower equivalent to that of all human brains combined

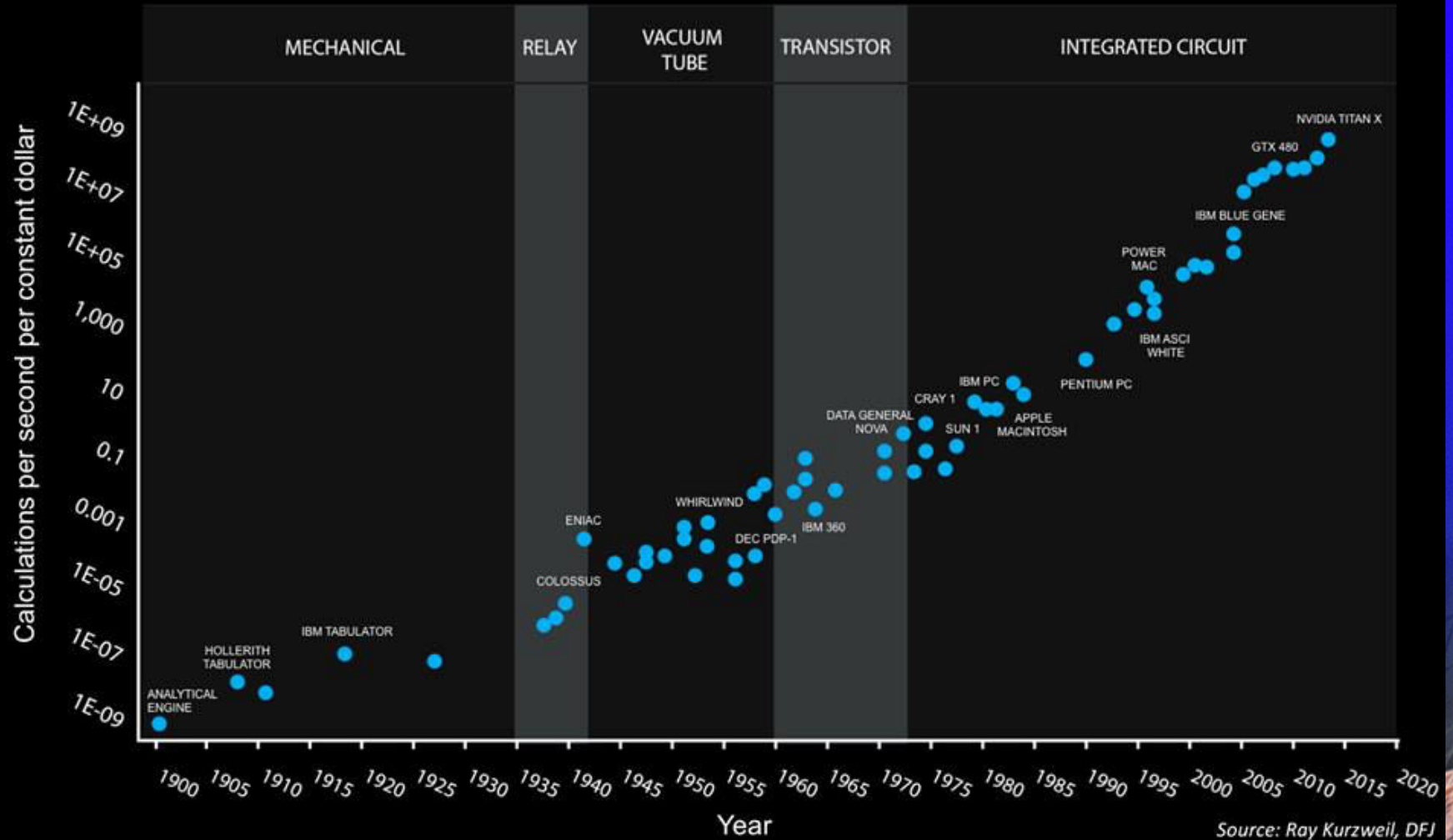
Surpasses brainpower of human in 2023

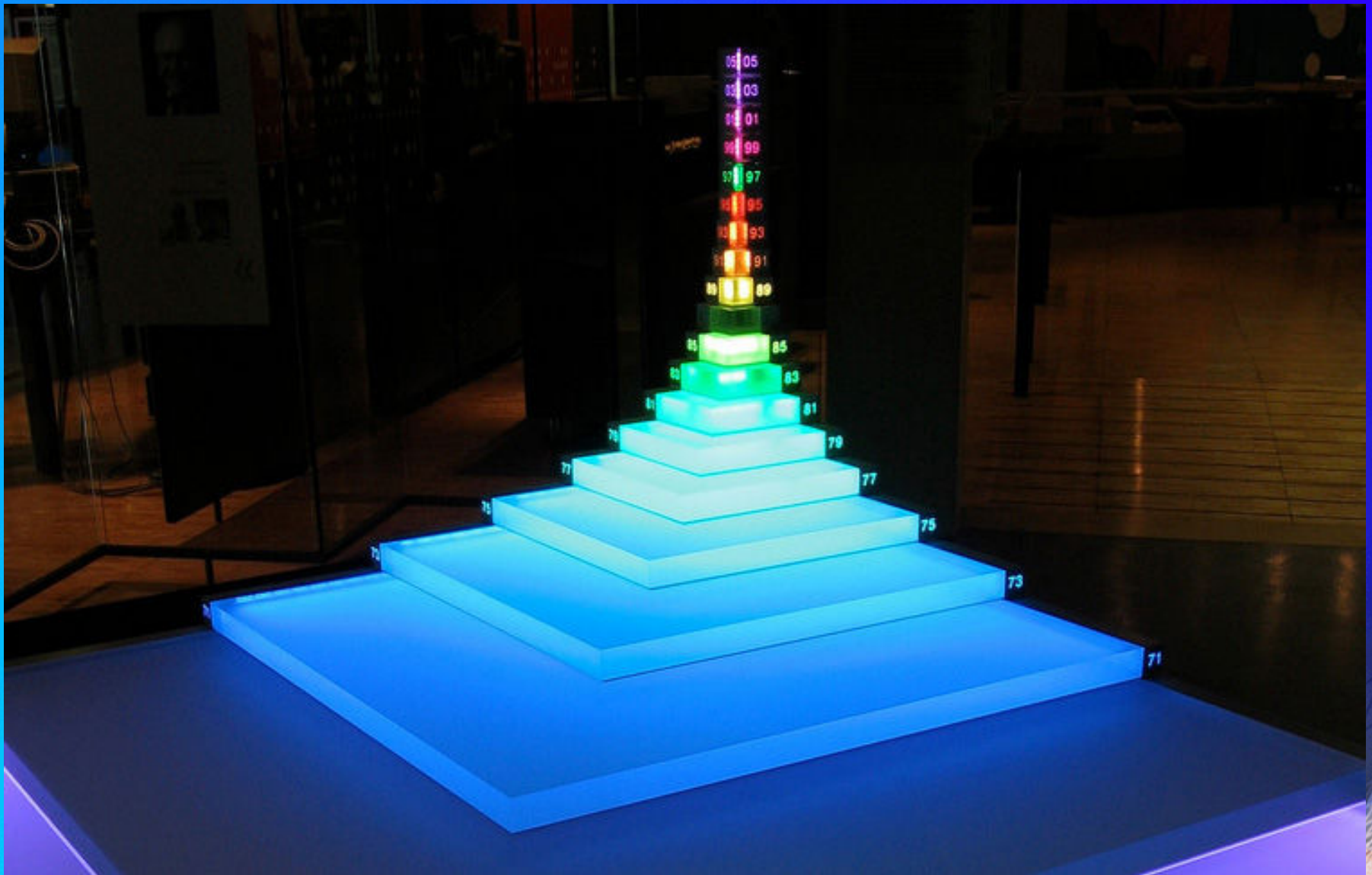


Surpasses brainpower of mouse in 2015

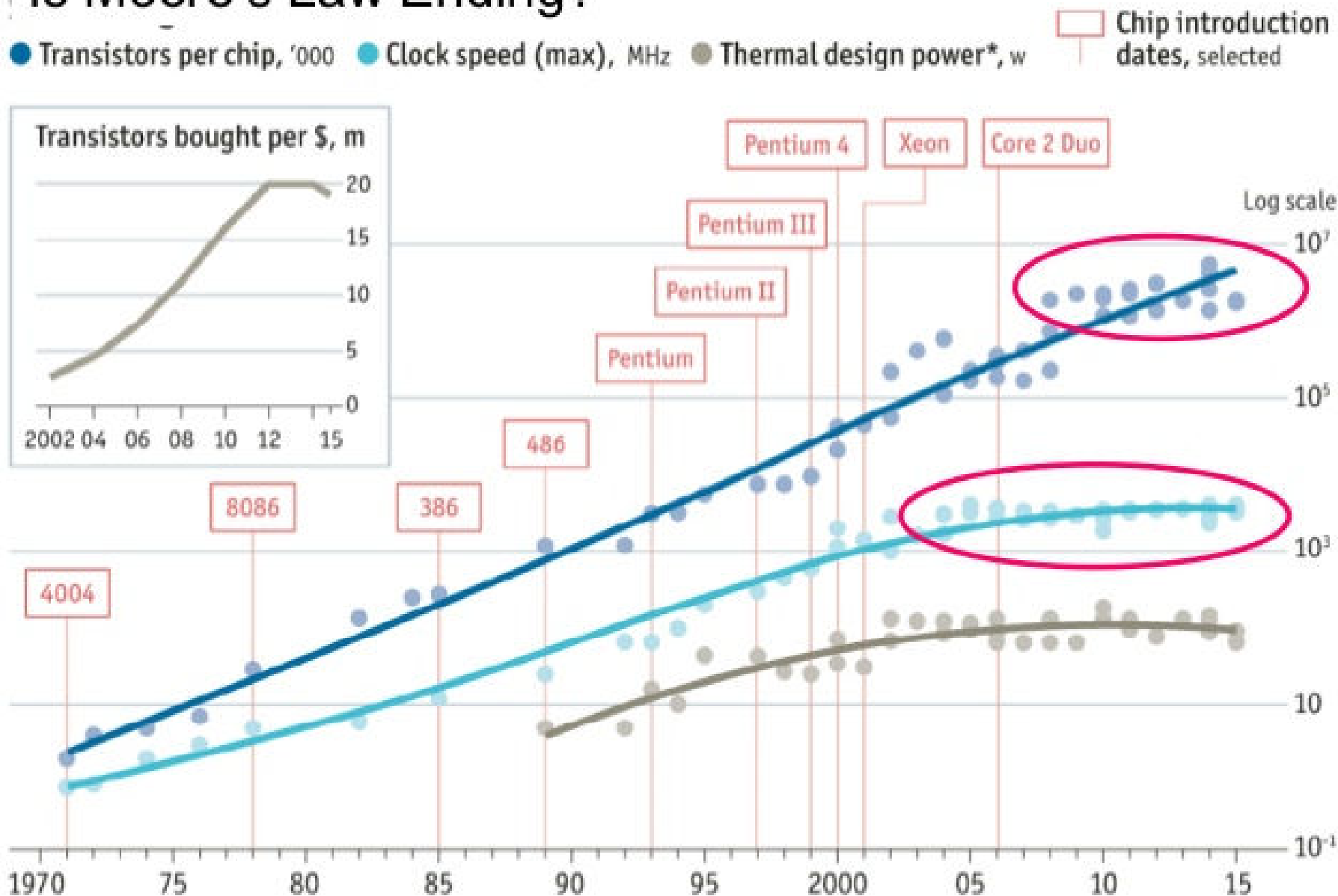


120 Years of Moore's Law





Is Moore's Law Ending?

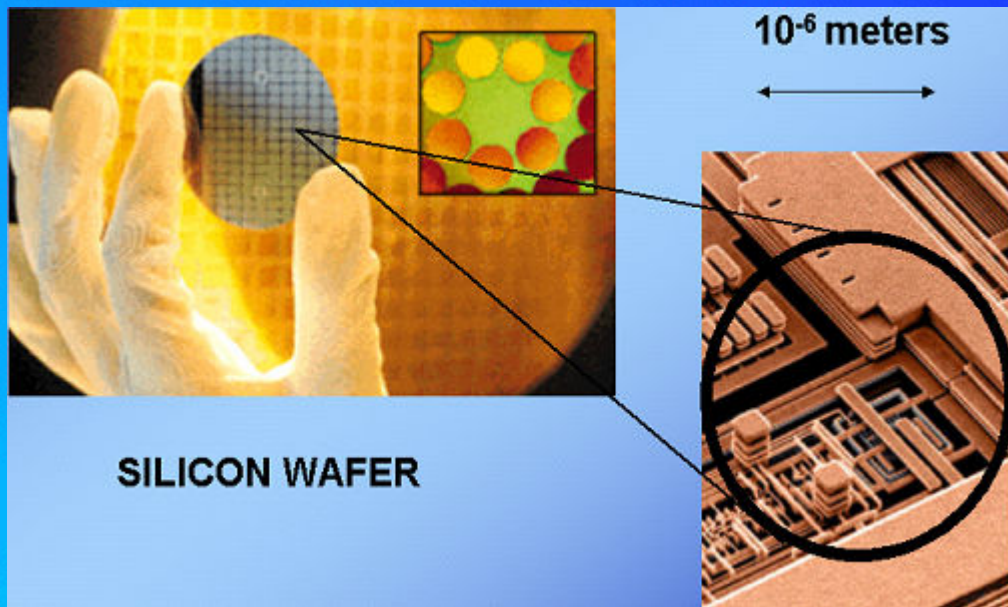


Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*

*Maximum safe power consumption

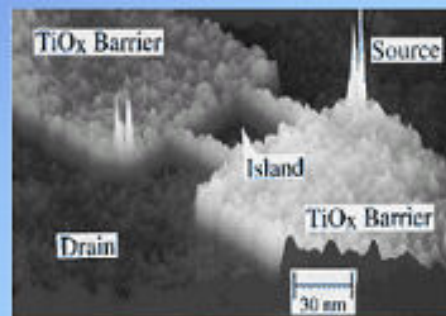
Economist, March 12-18, 2016

经典计算机发展状况



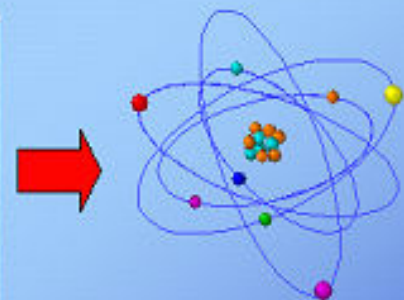
10^{-6} meters

TODAY



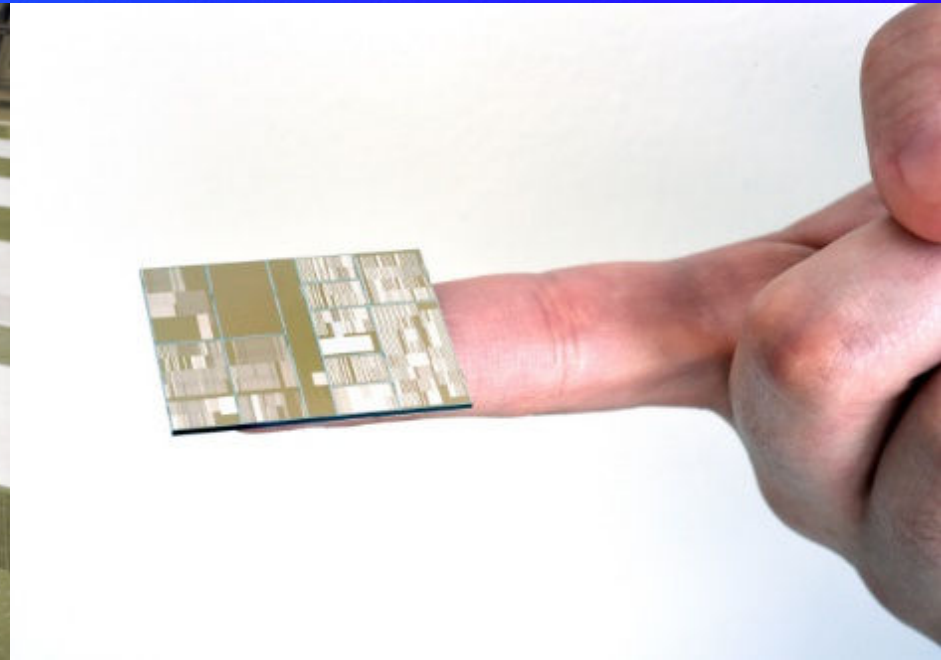
10^{-8} meters

TOMORROW



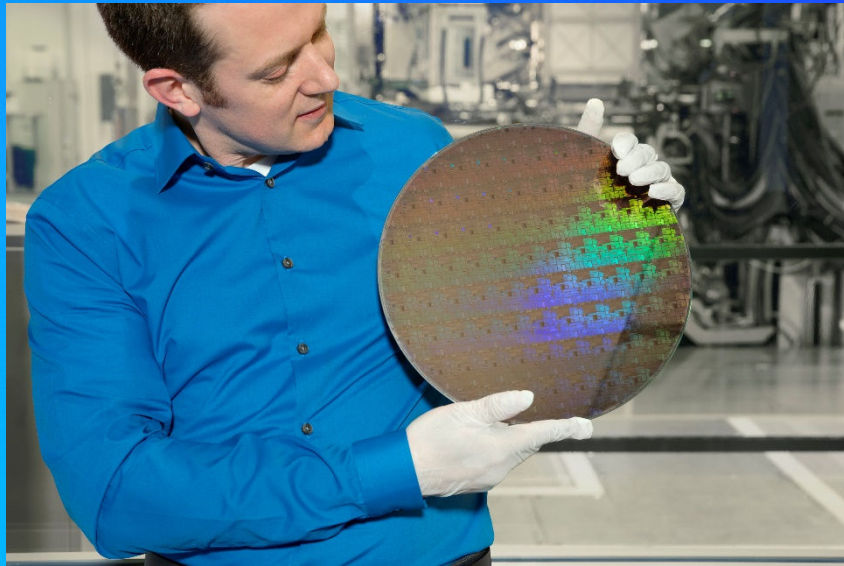
10^{-10} meters

IBM 7nm chip



Beyond silicon: IBM unveils world's first 7nm chip
With a silicon-germanium channel and EUV lithography(**extreme ultraviolet lithography**), IBM crosses the 10nm barrier. –July 2015

IBM 技术

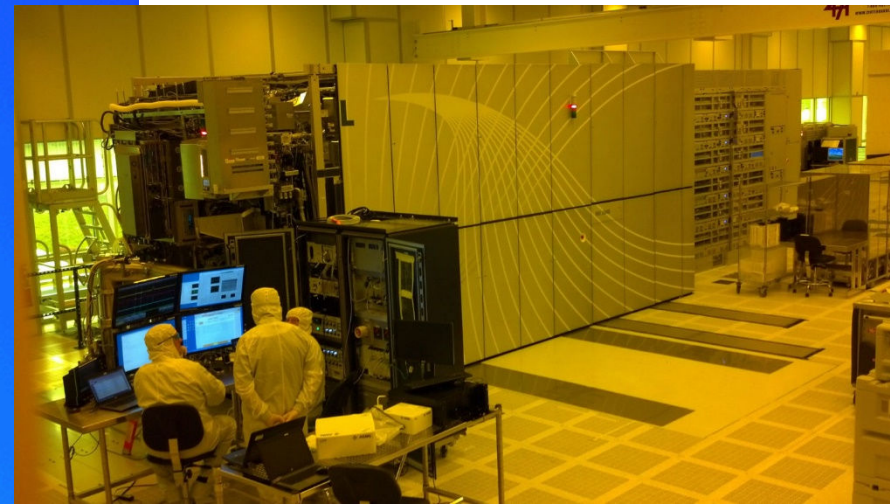
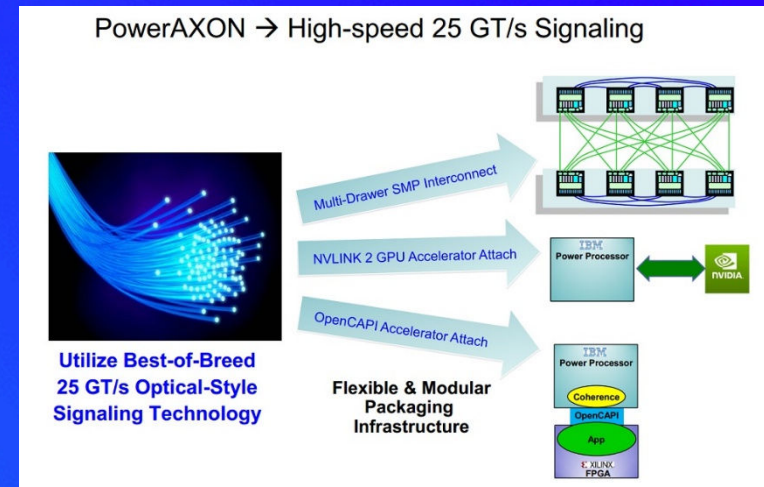


20 billion transistors
30 billion transistors

05 Jun 2017

Wafer of chips with 5nm silicon nanosheet transistors

IBM Research scientist Nicolas Loubet holds a wafer of chips with 5nm silicon nanosheet transistors manufactured using an industry-first process that can deliver 40 percent performance enhancement at fixed power, or 75 percent power savings at matched performance. (Credit: Connie Zhou)



6 May 2021

IBM 技术 2nm

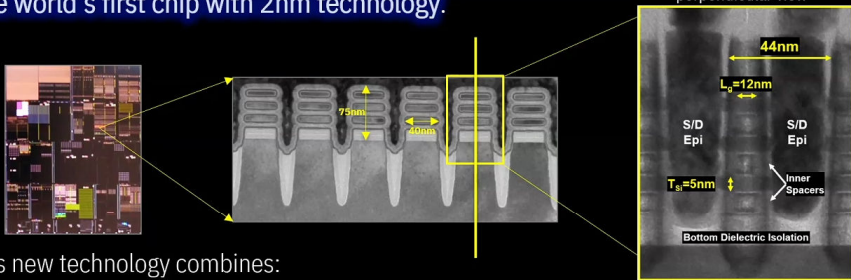
According to IBM, the new 2nm process is capable of fitting 50 billion transistors on a chip the size of a fingernail—up from the 30 billion transistors on the 5nm node.

<https://www.pcmag.com/news/ibm-unveils-2-nanometer-chip-process-but-actual-products-are-still-years>

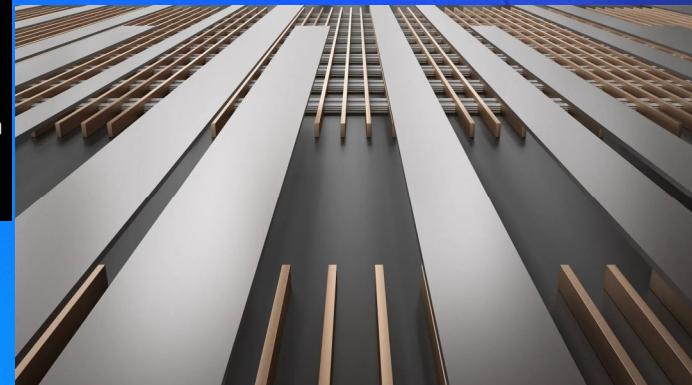
The potential benefits of these advanced 2 nm chips could include:

- **Quadrupling cell phone battery life**, only requiring users to charge their devices every four days.
- **Slashing the carbon footprint of data centers**, which account for one percent of global energy use. Changing all of their servers to 2 nm-based processors could potentially reduce that number significantly.
- **Drastically speeding up a laptop's functions**, ranging from quicker processing in applications, to assisting in language translation more easily, to faster internet access.
- **Contributing to faster object detection** and reaction time in autonomous vehicles like self-driving cars.

- IBM will announce a *new breakthrough* in semiconductor scaling, the world's first chip with 2nm technology.



- This new technology combines:
 - An industry-first **Bottom Dielectric Isolation** to enable 12nm gate length
 - A 2nd generation **Inner Spacer dry process** for precise gate control
 - **EUV patterning** to produce variable Nanosheet widths from 15nm to 70nm
 - A novel **Multi-Vt scheme** for both SoC and HPC applications
- Expected to offer 45% performance improvement or 75% power reduction compared to 7nm



20 Oct. 2023

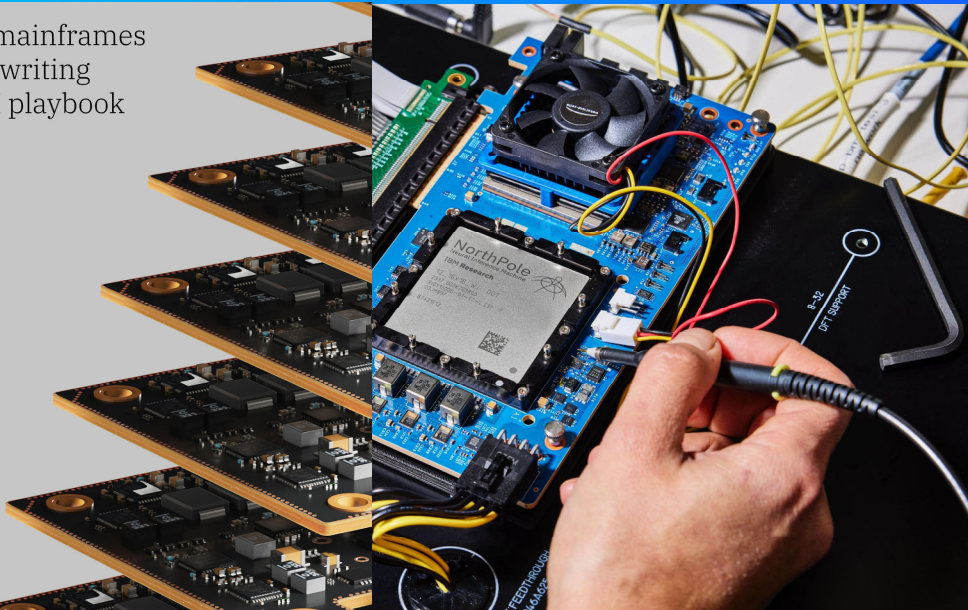
IBM 技术 AI Chip

A new chip architecture points to faster, more energy-efficient AI

The first promising set of results from NorthPole chips were published today in Science. NorthPole is a breakthrough in chip architecture that delivers massive improvements in energy, space, and time efficiencies, according to Modha. Using the ResNet-50 model as a benchmark, NorthPole is considerably more efficient than common 12-nm GPUs and 14-nm CPUs. (NorthPole itself is built on 12 nm node processing technology.) In both cases, NorthPole is 25 times more energy efficient, when it comes to the number of frames interpreted per joule of power required. NorthPole also outperformed in latency, as well as space required to compute, in terms of frames interpreted per second per billion transistors required. According to Modha, on ResNet-50, NorthPole outperforms all major prevalent architectures — even those that use more advanced technology processes, such as a GPU implemented using a 4 nm process.

<https://research.ibm.com/blog/northpole-ibm-ai-chip>

How mainframes
are rewriting
the AI playbook

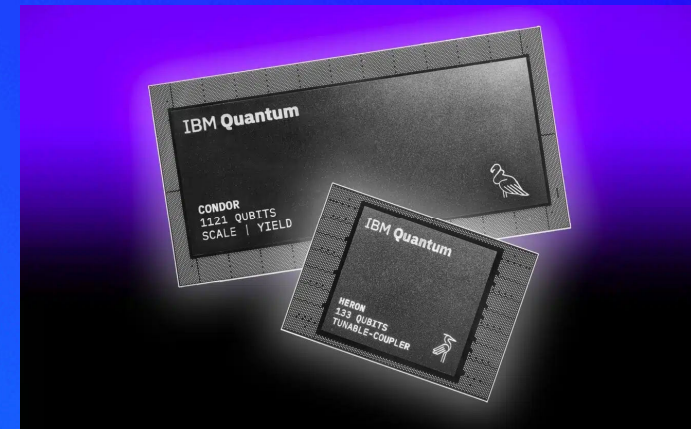


Since the birth of the semiconductor industry, computer chips have primarily followed the same basic structure, where the processing units and the memory storing the information to be processed are stored discretely. While this structure has allowed for simpler designs that have been able to scale well over the decades, it's created what's called **the von Neumann bottleneck**, where **it takes time and energy to continually shuffle data back and forth between memory, processing, and any other devices within a chip**. The work by IBM Research's Dharmendra Modha and his colleagues aims to change this, taking inspiration from how the brain computes. **"It forges a completely different path from the von Neumann architecture,"** according to Modha.

IBM Quantum

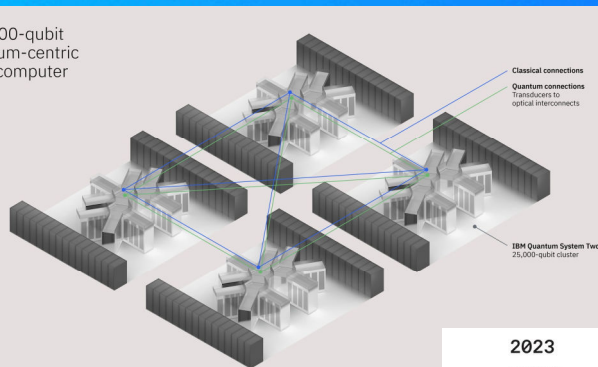
At IBM Quantum Summit 2023, **'IBM Quantum Heron'** was released as IBM's best performing quantum processor to date, with newly built architecture offering up to five-fold improvement in error reduction. (Credit: Christopher Tirrell for IBM)

IBM Heron is the first in IBM's new class of performant processors with significantly improved error rates, offering a five-times improvement over the previous best records set by IBM Eagle.

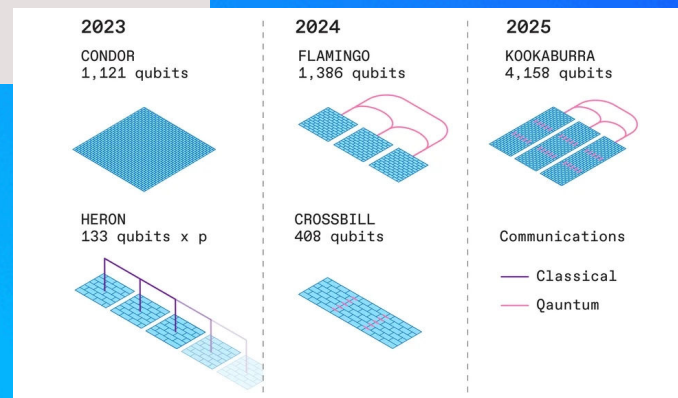


We've added a new dimension to our roadmap: the innovation roadmap, calling out key advances required to bring about error-corrected quantum computing at scale. After demonstrating Condor, our 1,121-qubit concept processor in 2023, we'll now focus on modular scaling by introducing l- and m-couplers with Flamingo and Crossbill, and in 2026, c-couplers with Kookaburra. These new breakthroughs will put us on course for an error-corrected quantum system running 100 million gates by 2029 and a billion gates by 2033.

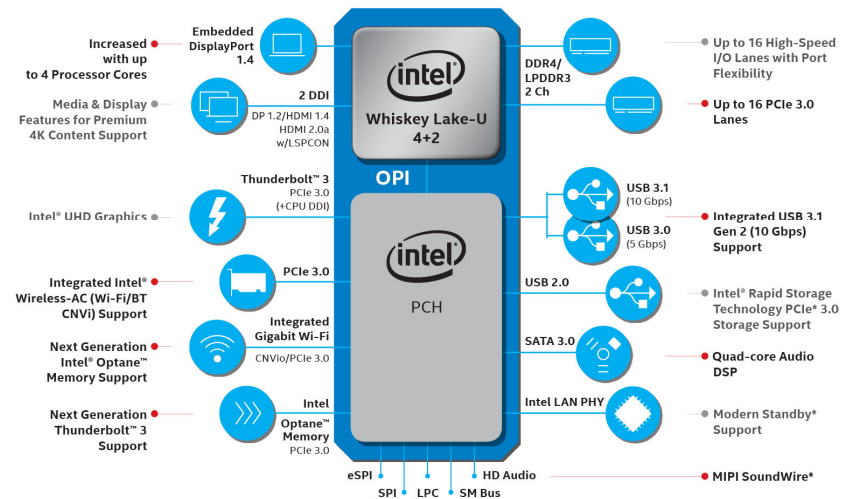
100,000-qubit
quantum-centric
supercomputer
—
2033



A visual rendering of IBM Quantum's 100,000-qubit quantum-centric supercomputer, expected to be deployed by 2033. (Credit: IBM)



WHISKEY LAKE U PLATFORM OVERVIEW



An Intel wafer. Chipmakers may find it more difficult to justify the huge costs of developing the next generations of chip technology.



华为计算



AI计算

面向“端、边、云”的全场景AI基础设施



Atlas 900 AI集群

Atlas 800 AI服务器



Atlas 200
AI加速模块



Atlas 200 DK
开发者套件



Atlas 300
推理卡



Atlas 500
智能小站



TaiShan服务器

基于鲲鹏处理器的新一代数据中心服务器，适合为大数据、分布式存储、高性能计算和数据库等应用高效加速。



鲲鹏服务器主板

基于鲲鹏处理器的数据中心服务器主板，帮助合作伙伴快速开发自有品牌的服务器产品。



AI模块

在端侧实现目标识别、图像分类等，广泛用于智能摄像机、机器人、无人机等端侧AI场景。

[Atlas 2001 DK开发者套件 >](#)
[Atlas 2001 A2 加速模块 >](#)



AI加速卡

提供AI推理、视频分析等功能，支持检索聚类、OCR识别、语音分析、视频分析等场景。

[Atlas 3001 Pro 推理卡 >](#)
[Atlas 3001 Duo 推理卡 >](#)
[Atlas 300V 视频解析卡 >](#)
[Atlas 300V Pro 视频解析卡 >](#)



智能边缘

具有超强计算性能、体积小、环境适应性强、易于维护等特点，可以在边缘场景广泛部署。

[Atlas 500 A2 智能小站 >](#)
[Atlas 500 Pro 智能边缘服务器\(型号: 3000\) >](#)

华为麒麟9000

关键特性

Process

- 5nm

CPU

- 1 x Cortex-A77@ 3.13 GHz
- 3 x Cortex-A77@ 2.54 GHz
- 4 x Cortex-A55@2.05 GHz

GPU

- 24-core Mali-G78, Kirin Gaming+ 3.0

AI

- HUAWEI Da Vinci Architecture 2.0
- Ascend Lite*2+Ascend Tiny*1

5G

- SA&NSA,Sub-6G&mmWave

ISP

- Kirin ISP 6.0,Quad-pipeline

System Cache

- 8MB

Memory

- LPDDR 5/4X



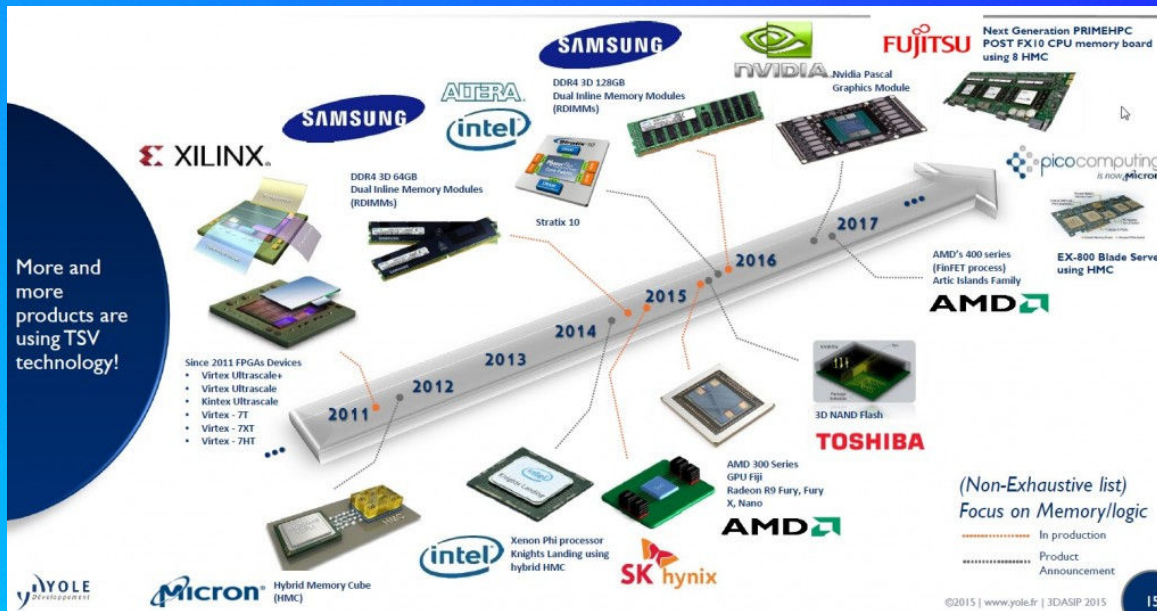
麒麟9000采用全球顶级5nm工艺制程，集成153亿晶体管，更小尺寸蕴藏更大能量。麒麟9000是业界最成熟的5G SA解决方案，带给用户疾速的5G现网体验。麒麟9000全新升级Cortex-A77 CPU，大核主频突破3.1GHz，爆发性能实力。24-core Mali-G78 GPU与Kirin Gaming+ 3.0强强联手，打造更畅快更省电的高画质游戏体验。麒麟9000升级华为达芬奇架构2.0 NPU，大核彰显出众AI算力，探索更丰富的AI视频应用，NPU微核实现更优能效比，全天超低功耗运行，解锁更多体验。影像方面，麒麟9000升级Kirin ISP 6.0，业界首次实现ISP+NPU融合架构，具备实时包围曝光HDR视频合成能力，手机拍摄暗光和逆光视频更清晰，细节展现淋漓尽致。

华为智驾



相关技术

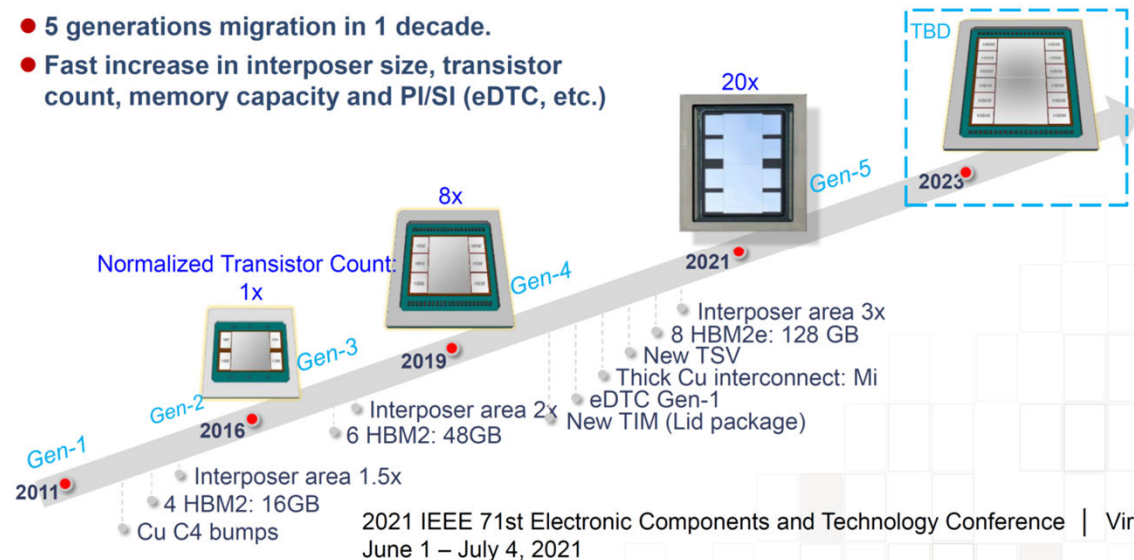
Memory Architecture – 3D TSV Memory Packaging



22

CoWoS®-S Rapid Progress

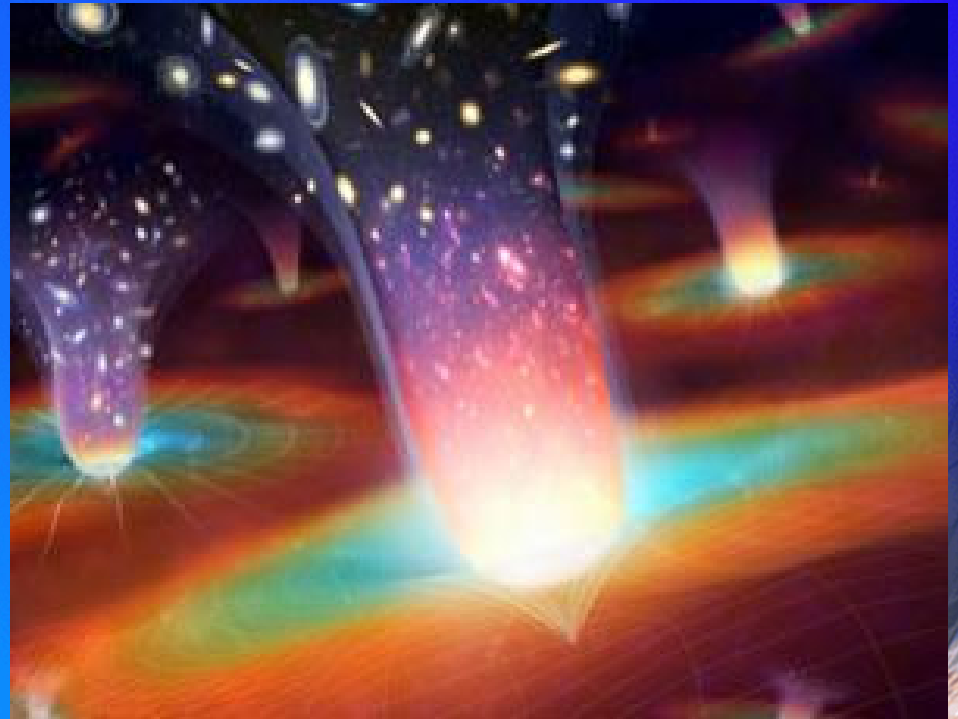
- 5 generations migration in 1 decade.
- Fast increase in interposer size, transistor count, memory capacity and PI/SI (eDTC, etc.)



What is quantum information?



“Information is physical.” 1960s *by Rolf Landauer*
from IBM Research



Quantum information is that kind of information which is carried by quantum systems from the preparation device to the measuring apparatus in a quantum mechanical experiment. *by R.F. Werner*

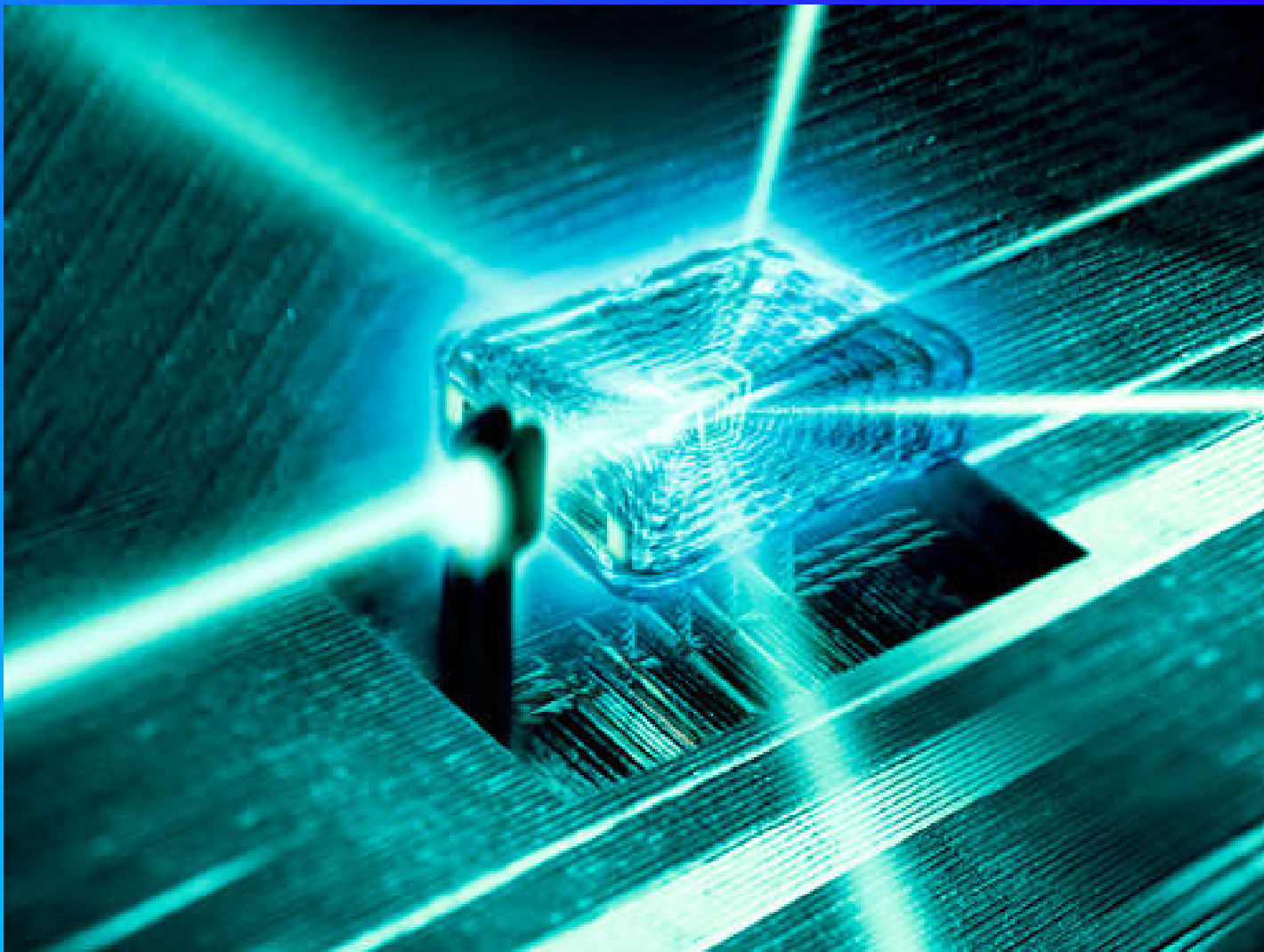
from New Scientist



Getting inside the mind of God

from New Scientist

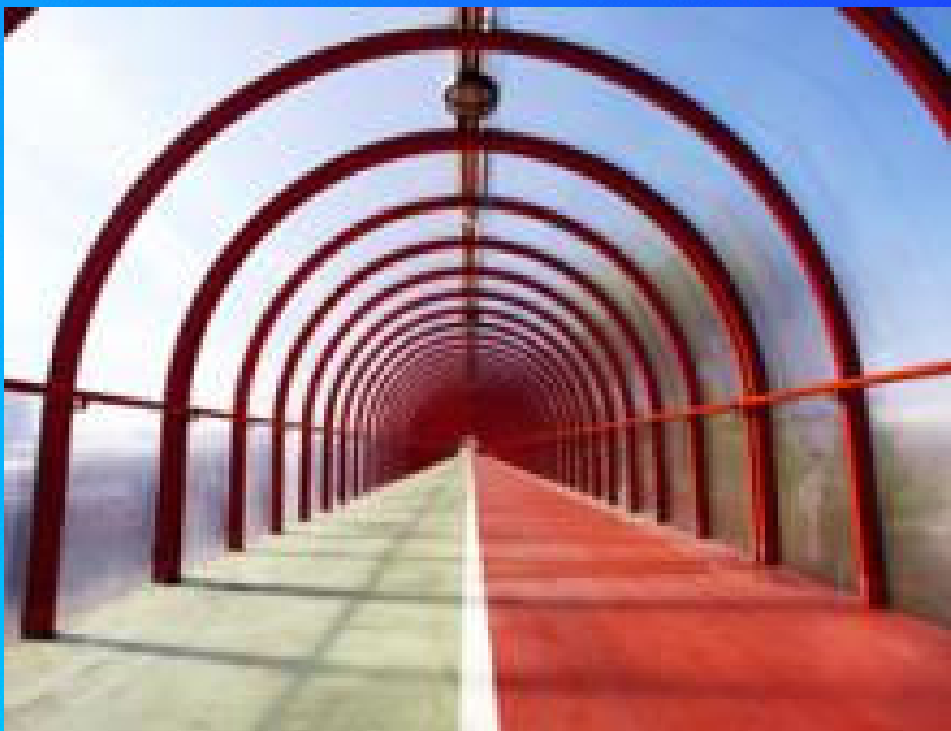




If we can harness the fuzziness of quantum entities to crunch vast amounts of data instantaneously, the sky will be no limit. **Vlatko Vedral** is your guide

Image: Richard Kail/Science Photo Library

from New Scientist



Spooky action at a distance



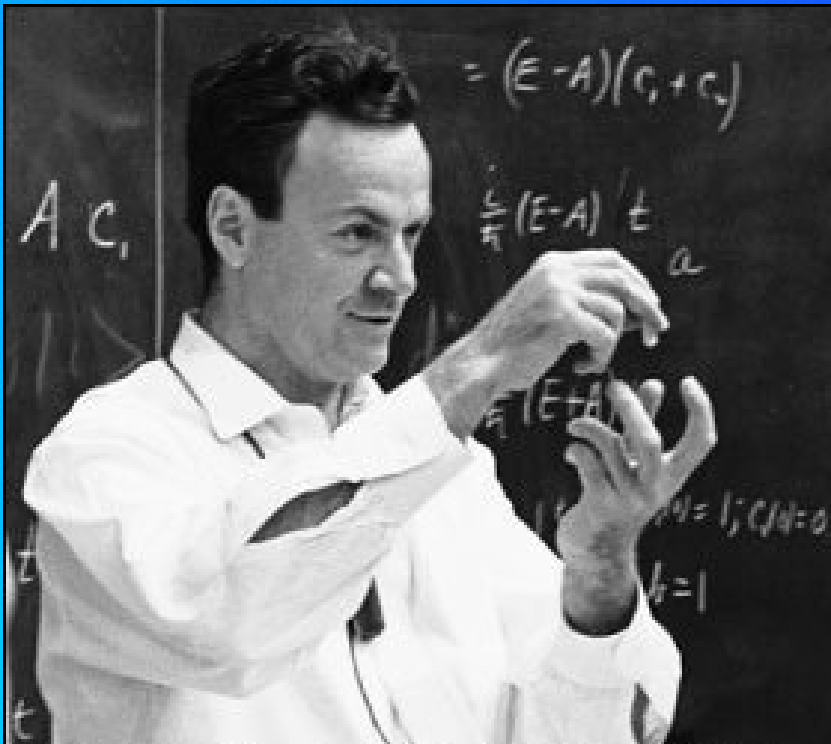
Wave-Particle Duality

from New Scientist

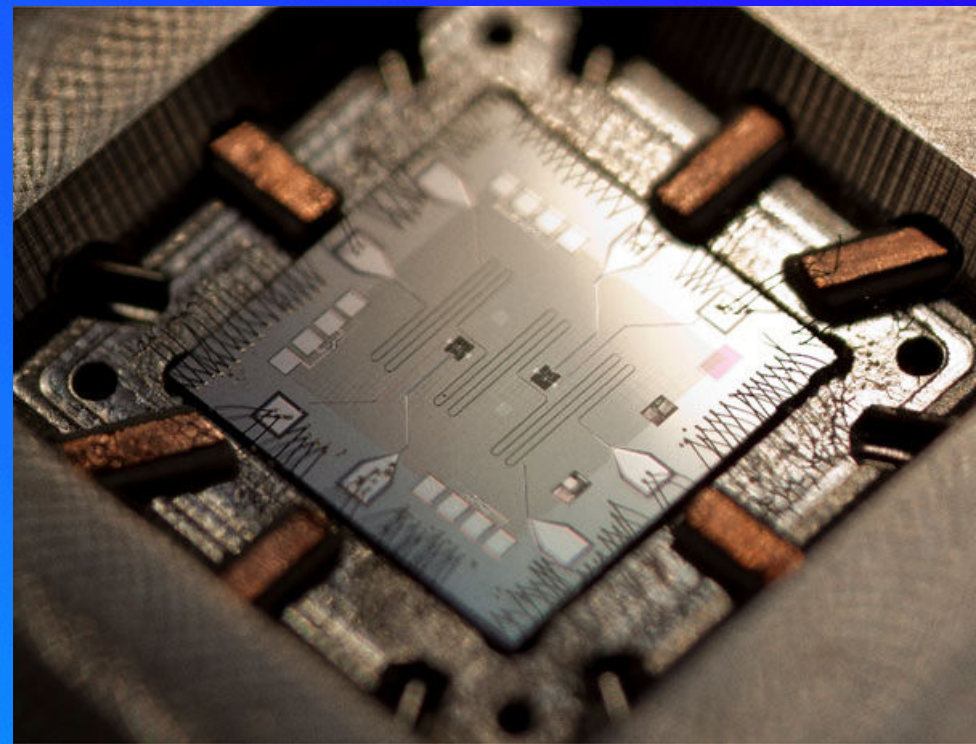
“There is plenty of room at the bottom.” (Dec 29, 1959)

“It seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds dominant sway.”

— — Richard P. Feynman (1985)



Nobel prize 1965



from New Scientist



量子世界

(Max Planck)



$$E = \frac{hc}{\lambda}$$

$$E = mc^2$$

(Albert Einstein)

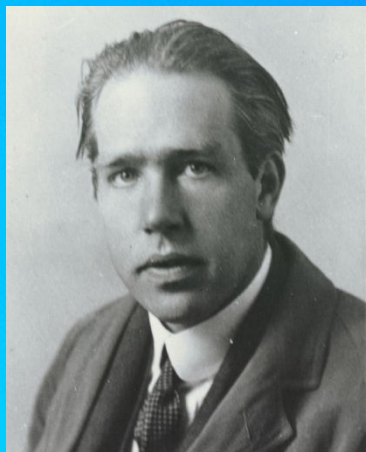


(Louis de Broglie)



$$\lambda = \frac{h}{mc}$$

互补性和不确定原理



(Niels Bohr)

中国科学技术大学 陈凯



(Werner Heisenberg)

量子测量 塌缩



经典和量子比特

经典和量子信息处理中的本质不同在于存贮和处理信息的方式

在经典信息处理中，信息是由宏观的比特来表示通常取值为二进制的值
0 或者 1

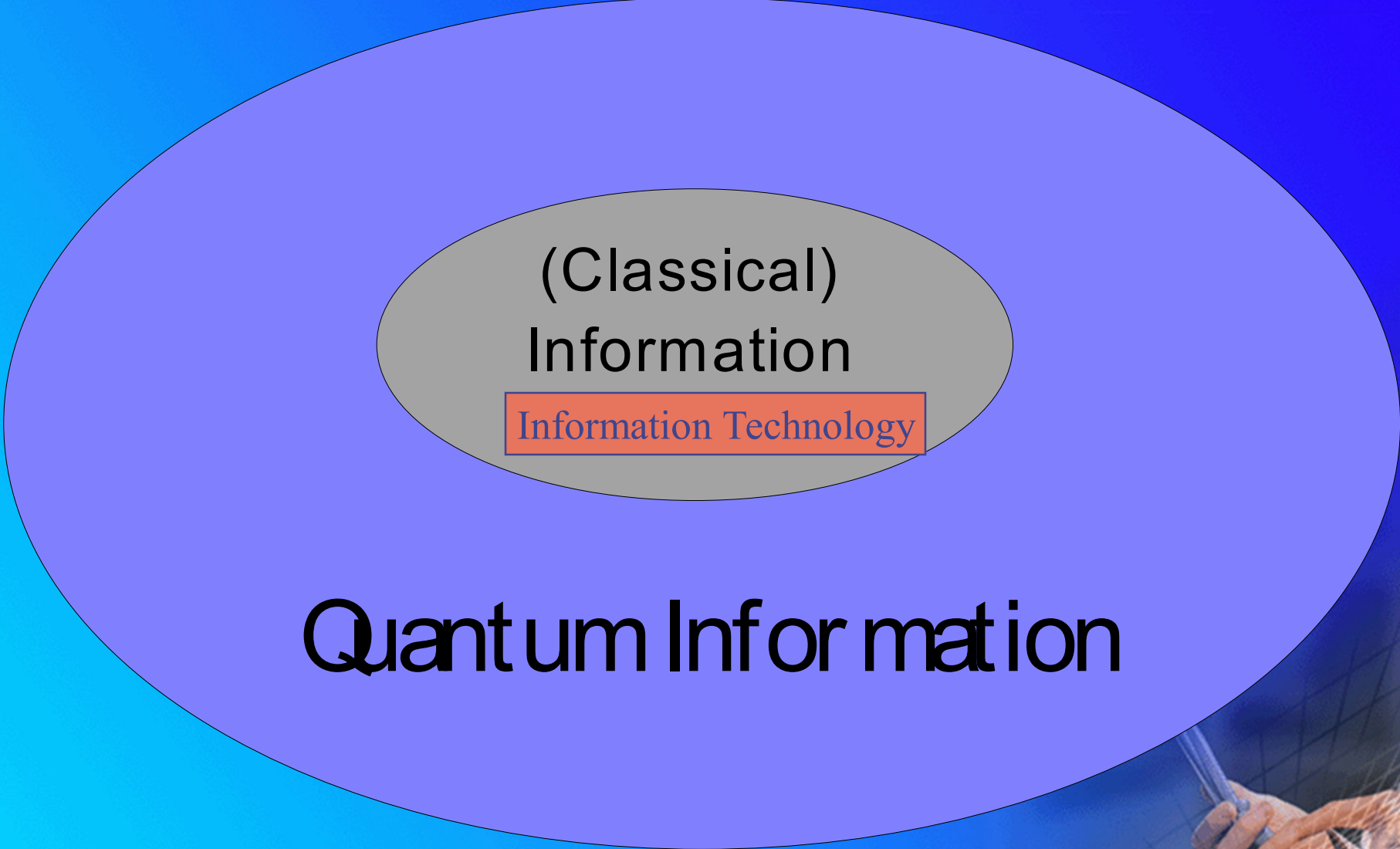
在量子信息处理中，信息是由微观的量子比特来表征，通常取值不可数的多值形式

$$\alpha|0\rangle + \beta|1\rangle$$

其中 α, β 其中为满足下式的任意两个复数

$$|\alpha|^2 + |\beta|^2 = 1.$$





A Venn diagram with a large light blue oval containing a smaller grey oval. The grey oval contains the text "(Classical) Information" and a red box with "Information Technology". The large blue oval contains the text "Quantum Information".

(Classical)
Information

Information Technology

Quantum Information

量子信息处理的概念和内涵

- ◆ 量子信息处理是指以量子力学基本原理为基础、利用量子态的相干特性来编码、传输和操控信息，进而实现量子计算、量子通信、量子精密测量、量子模拟等功能的全新信息处理方式。
- ◆ 由于携带量子信息的载体可以工作在原子分子层次上，从而只需要损耗更少的能量来进行处理、存储和传输。
- ◆ 是经典信息处理的大幅拓展，探索和发展更有效地进行计算、通信、测量等方式

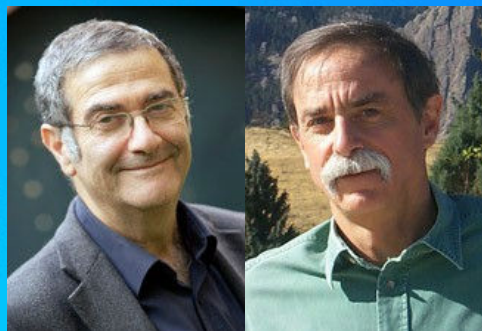
量子信息的重要科学意义



- Roy J. Glauber 由于在量子光学理论及其在量子信息科学应用上的重要贡献获2005年诺贝尔物理学奖



- Anton Zeilinger等由于在量子物理和量子信息领域重要的实验成就获2010年沃尔夫物理学奖



- Serge Haroche和David Wineland由于在量子系统测量与操控及其在量子信息科学应用上的重要贡献获2012年诺贝尔物理学奖

- Peter Zoller和Ignacio Cirac由于在量子信息、量子光学和冷原子物理领域的开创性理论贡献获2013年沃尔夫物理学奖



Press release: The Nobel Prize in Physics 2022

English

[English \(pdf\)](#)

Swedish

[Swedish \(pdf\)](#)



4 October 2022

[The Royal Swedish Academy of Sciences](#) has decided to award the Nobel Prize in Physics 2022 to

Alain Aspect

Institut d'Optique Graduate School – Université Paris-Saclay and École Polytechnique, Palaiseau, France

John F. Clauser

J.F. Clauser & Assoc., Walnut Creek, CA, USA

Anton Zeilinger

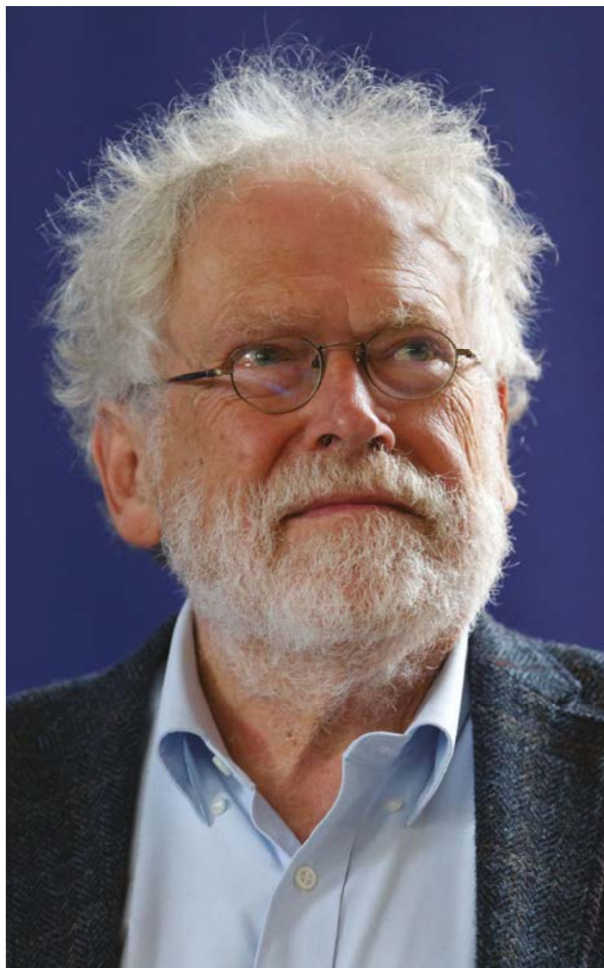
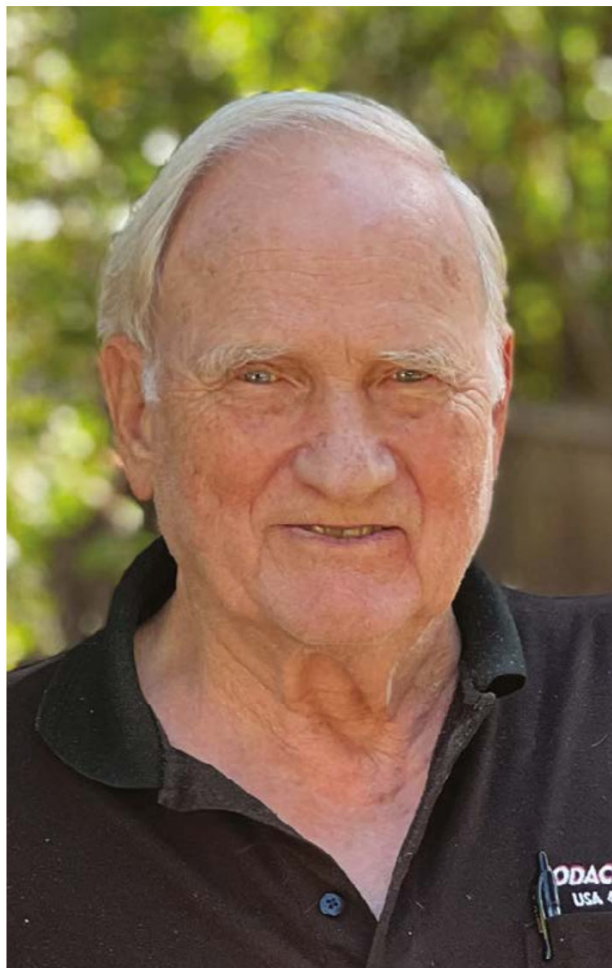
University of Vienna, Austria

“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

Entangled states – from theory to technology

Alain Aspect, John Clauser and Anton Zeilinger have each conducted groundbreaking experiments using entangled quantum states, where two particles behave like a single unit even when they are separated. Their results have cleared the way for new technology based upon quantum information.





From left: John Clauser, Anton Zeilinger and Alain Aspect won this year's physics Nobel prize.

Nature | Vol 610 | 13 October 2022 | 241

PHYSICS NOBEL FOR 'SPOOKY' QUANTUM ENTANGLEMENT

Award goes to three physicists whose research laid the groundwork for quantum information science.

量子信息处理

It's a “mystery”. THE mystery. We don't understand it, but we can tell you how it works. *(Feynman)*

量子信息发展史

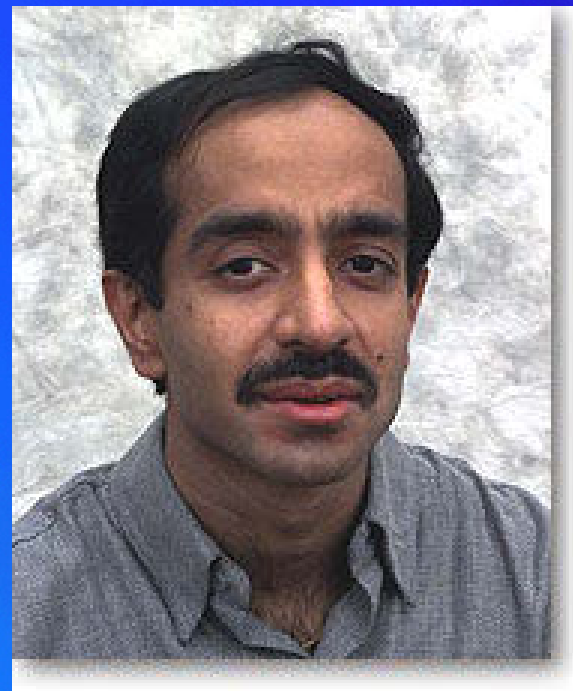


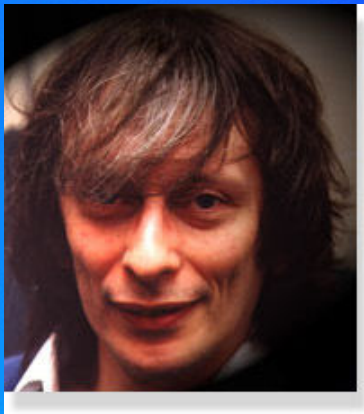
Peter Shor 算法(1994)

Lov Grover 算法(1997)



Seth Lloyd





Deutsch 普适量子计算
Deutsch –Jozsa 算法



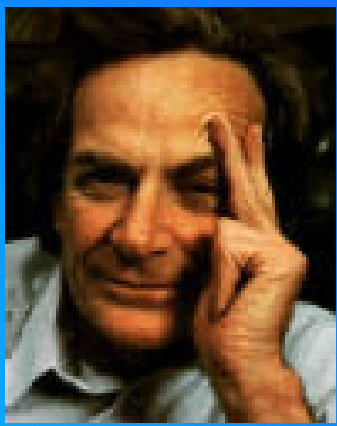
Ekert(E91 协议)
Steane 纠错码



Cirac, Zoller
量子信息理论



量子信息发展史



“There’s plenty of
room at the bottom”

(Richard Feynman)



(Paul Benioff)

Quantum Turing
machine

Quantum key
distribution
BB84

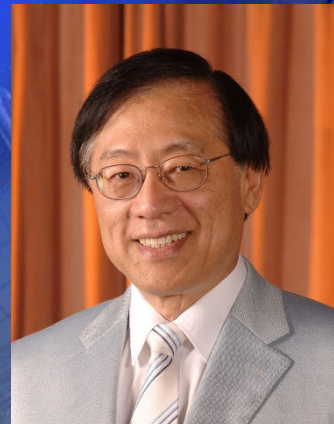


(David Deutsch)

Universal
QC

Quantum
Communication
Complexity

Andrew Chi-Chih Yao



(C. Bennett) (G. Brassard)

量子比特与量子纠缠

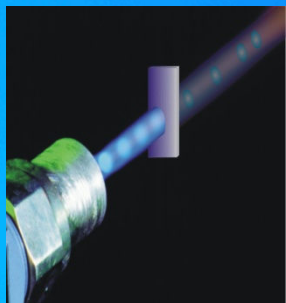
量子 物质最基本单元的物理描述

量子纠缠

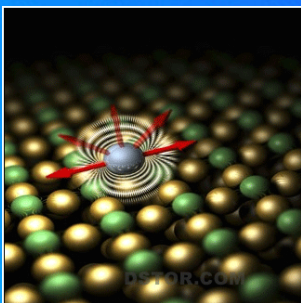
例如光量子，是传递电磁相互作用的基本粒子

不可分割

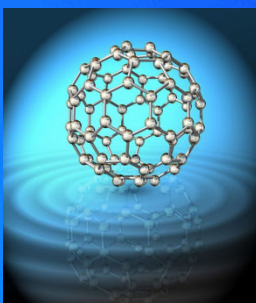
$$| \text{standing} \rangle + | \text{lying} \rangle$$



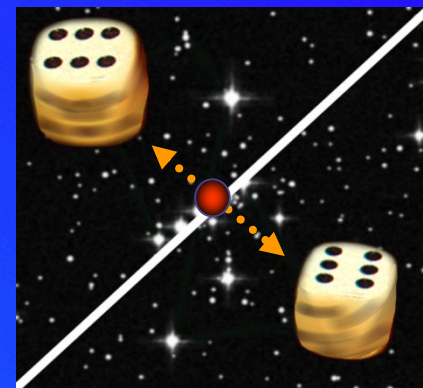
光子



原子



分子



遥远地点之间的惊人关联！

经典比特



0



1

量子比特

$|0\rangle$

$|1\rangle$

叠加态

$$| \text{standing} \rangle + | \text{lying} \rangle$$

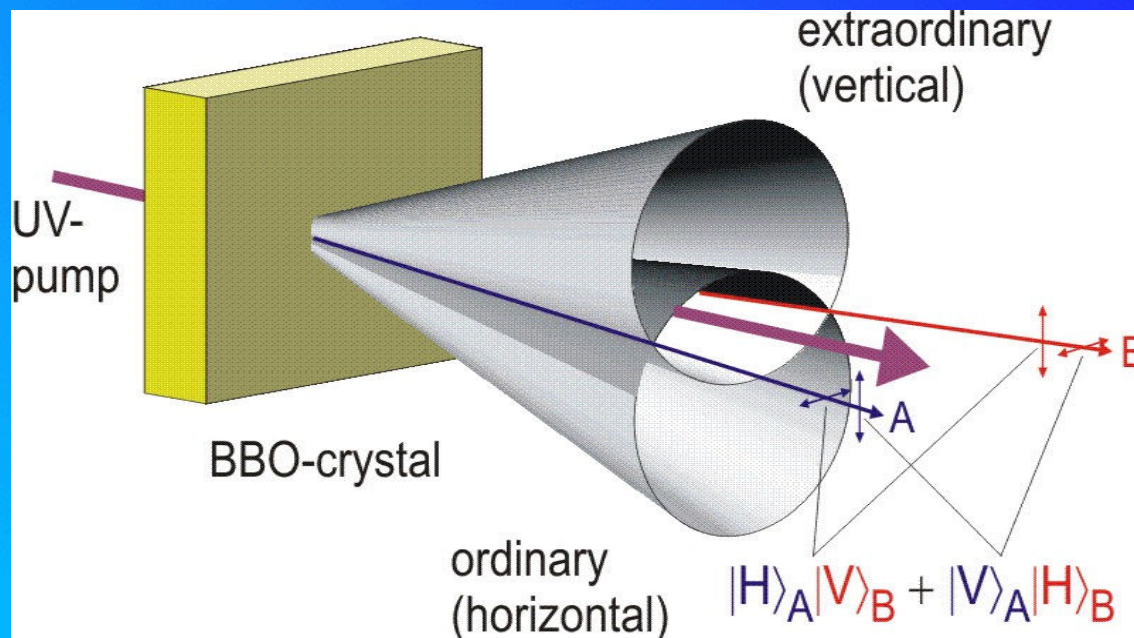
光子极化



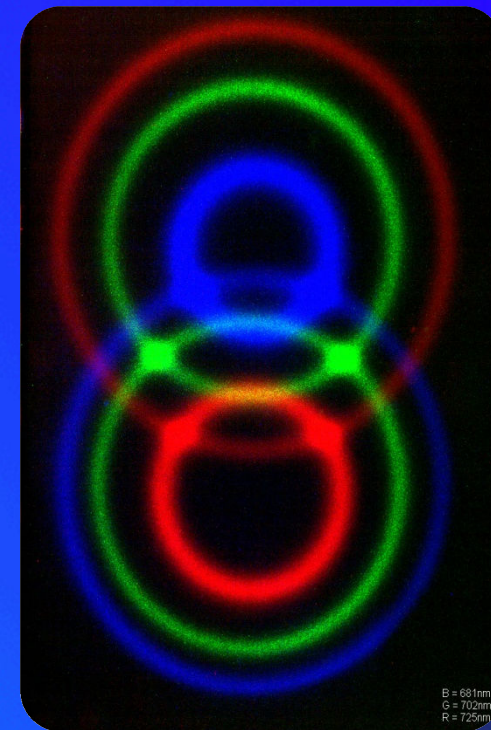
量子叠加



Polarization Entanglement Source



PDC



$$|\Phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1 |H\rangle_2 \pm |V\rangle_1 |V\rangle_2)$$

$$|\Psi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1 |V\rangle_2 \pm |V\rangle_1 |H\rangle_2)$$

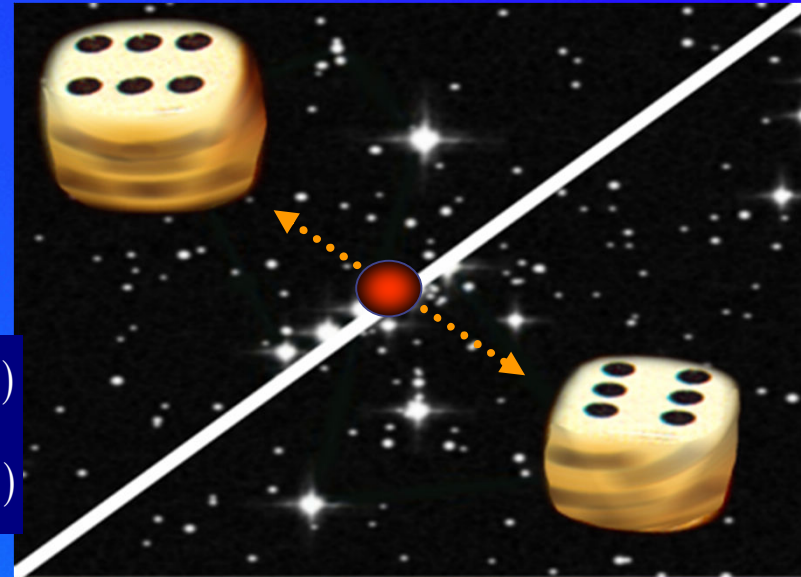
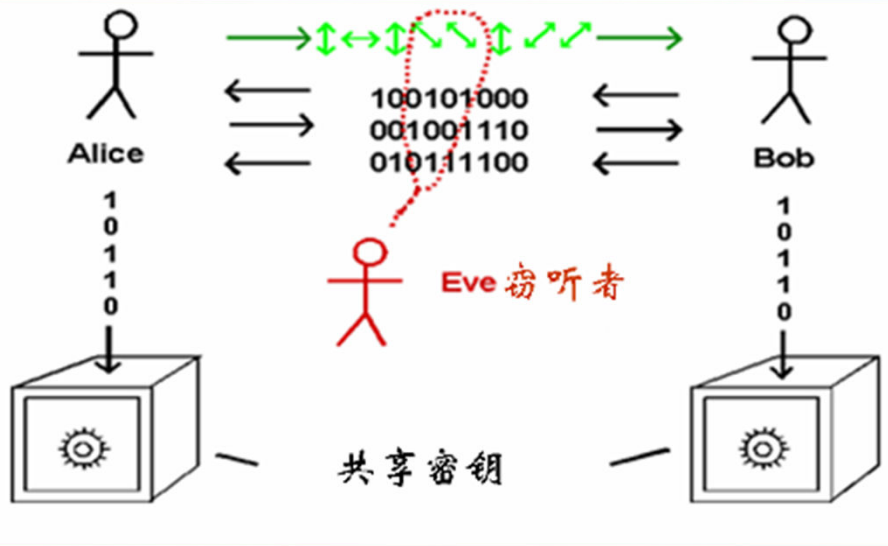
● P. G. Kwiat et al., Phys. Rev. Lett. 75, 4337 (1995)

量子通信技术:量子加密术

无条件安全的密钥生成

纠缠态方案

Ekert, PRL 67, 661 (1991)



单粒子方案
Bennett & Brassard (1984)

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|\leftrightarrow\rangle_1 |\leftrightarrow\rangle_2 \pm |\downarrow\rangle_1 |\downarrow\rangle_2)$$
$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|\leftrightarrow\rangle_1 |\downarrow\rangle_2 \pm |\downarrow\rangle_1 |\leftrightarrow\rangle_2)$$

量子不可克隆定理

量子不可分割

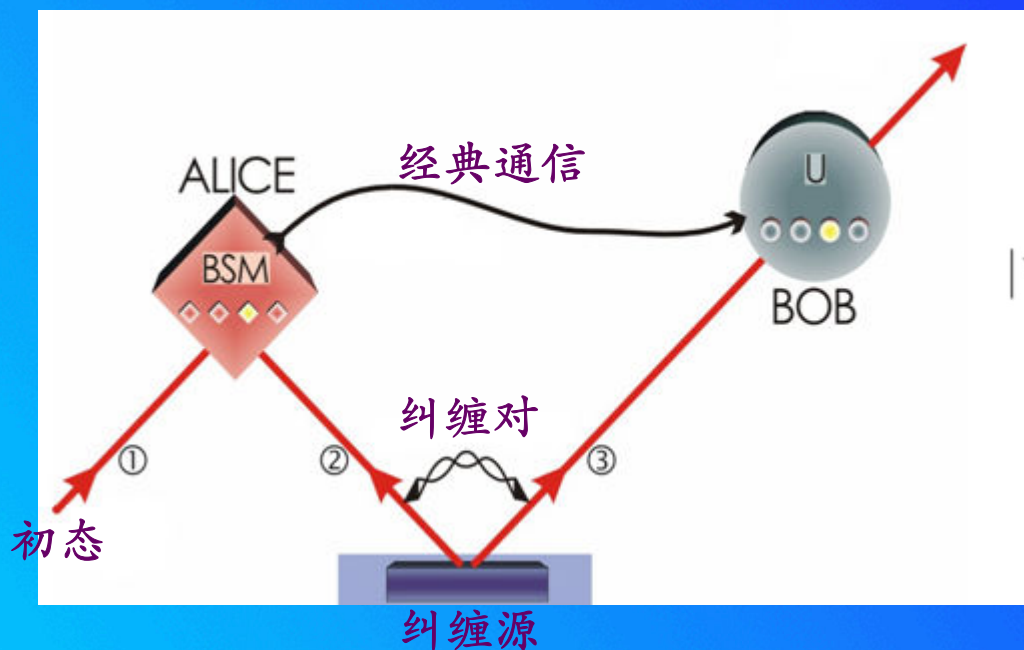
一次一密, 完全随机



无条件安全



量子通信技术:量子隐形传态

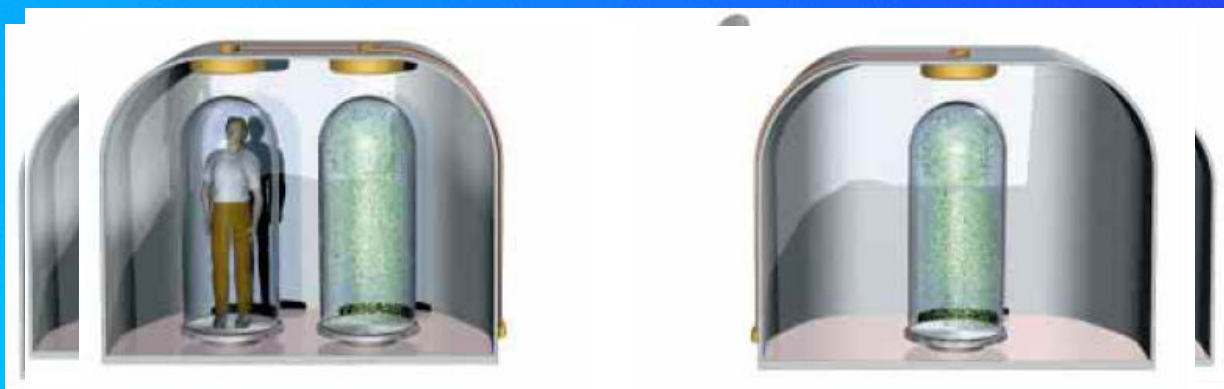


初态 $|\Phi\rangle_1 = \alpha|\leftrightarrow\rangle_1 + \beta|\uparrow\downarrow\rangle_1$

纠缠对 $|\Phi^+\rangle_{23}$

$$|\Psi\rangle_{123} = |\Phi^+\rangle_{12} \otimes (\alpha|\leftrightarrow\rangle_3 + \beta|\uparrow\downarrow\rangle_3) + |\Phi^-\rangle_{12} \otimes (\alpha|\leftrightarrow\rangle_3 - \beta|\uparrow\downarrow\rangle_3) + |\Psi^+\rangle_{12} \otimes (\alpha|\uparrow\downarrow\rangle_3 + \beta|\leftrightarrow\rangle_3) + |\Psi^-\rangle_{12} \otimes (\alpha|\uparrow\downarrow\rangle_3 - \beta|\leftrightarrow\rangle_3)$$

Bennett et al., PRL 73, 3801 (1993)



量子计算与量子通信

量子并行性

经典比特

0 或 1
00, 01, 10 或 11
000, 001, 010.....
:
:
:

量子比特

0 + 1
00 + 01 + 10 + 11
000 + 001 + 010 +
:
:
:

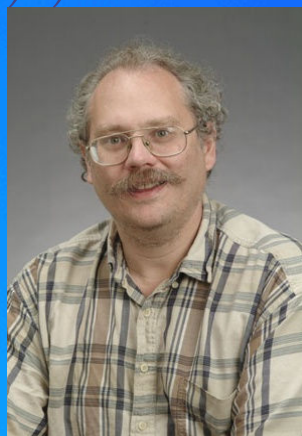
量子并行性使得量子计算机可以同时对 2^N 个数进行数学运算，其效果相当于经典计算机重复实施 2^N 次操作。

$$U \sum_{i=1}^{2^N} a_i |i\rangle = \sum_{i=1}^{2^N} a_i U|i\rangle, \quad 2^N!$$

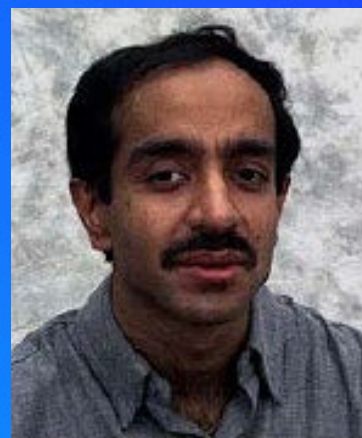
Shor算法

$$\text{Exp}(\sqrt[3]{\log(N)} \cdot \sqrt[3]{\log \log(N)^2} \cdot O(1)) \\ \Rightarrow O((\log(N))^3)$$

- ⌞ N比特整数，计算步数
- ⌞ 利用经典THz计算机分解300位的大数，需 10^{24} 步，**150000年**。
- ⌞ 利用Shor算法THz计算机，只需 10^{10} 步，**1秒**！
- ⌞ RSA将不再安全！



P. W. Shor

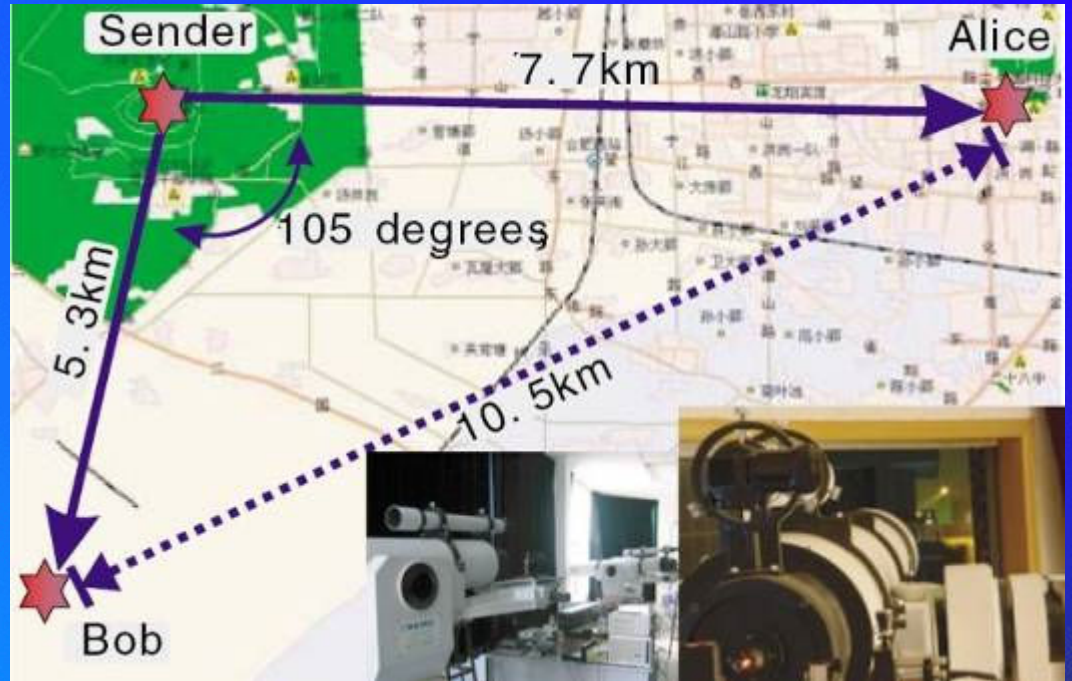
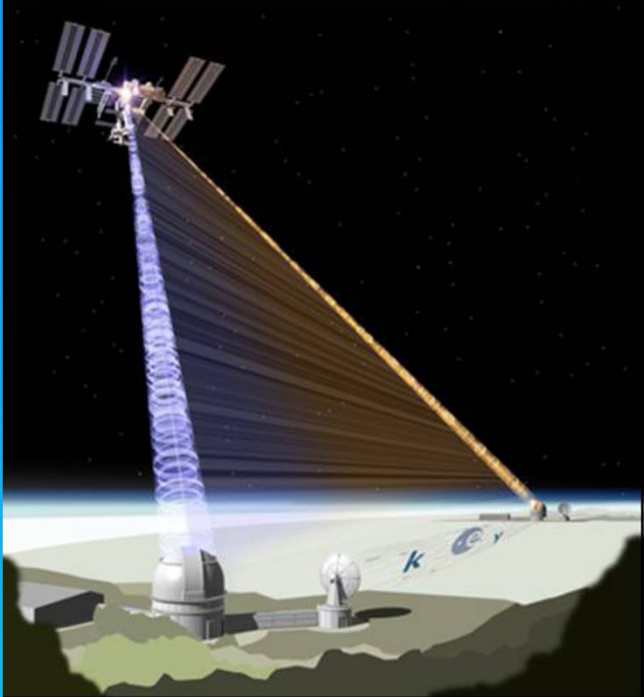


L. K. Grover

Grover搜寻算法

- ⌞ 如何在草堆中找到一根针？
- ⌞ 经典搜寻： N 步
- ⌞ 量子搜寻： $N^{1/2}$ 步
- ⌞ 可破译DES密码：
 2^{56} 个数中搜寻密钥
1000年 $\Rightarrow$ **4分钟**

远程量子通信： 自由空间纠缠光子分发

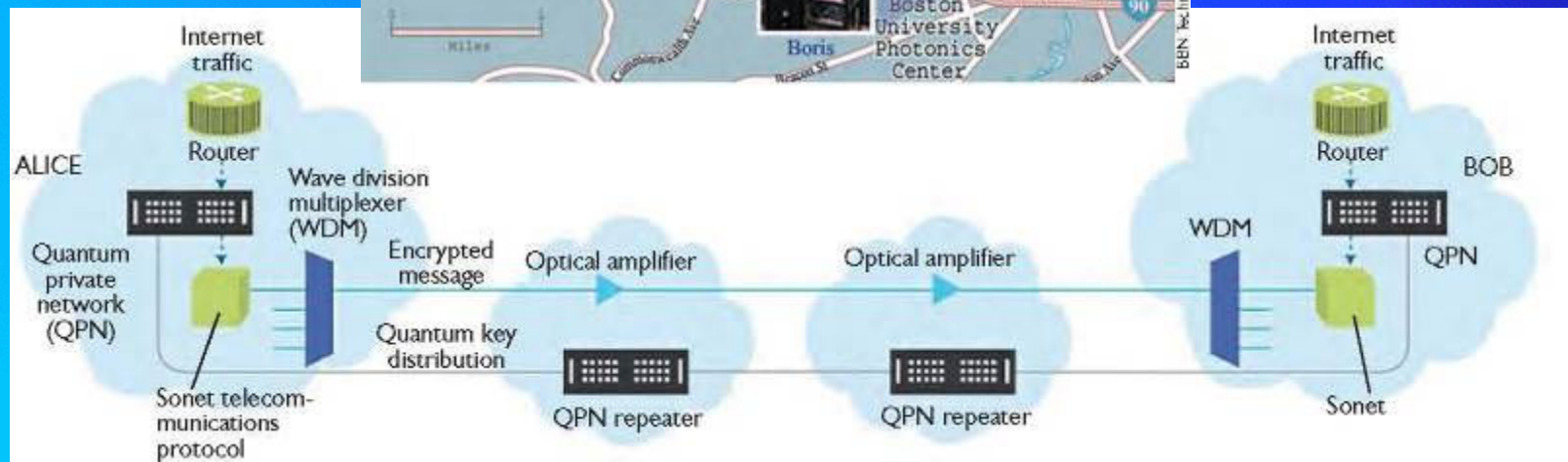


- 1km M. Aspelmeyer et al., Science 301, 621 (2003)
- 13km C.-Z. Peng et al., PRL 94, 150501 (2005)

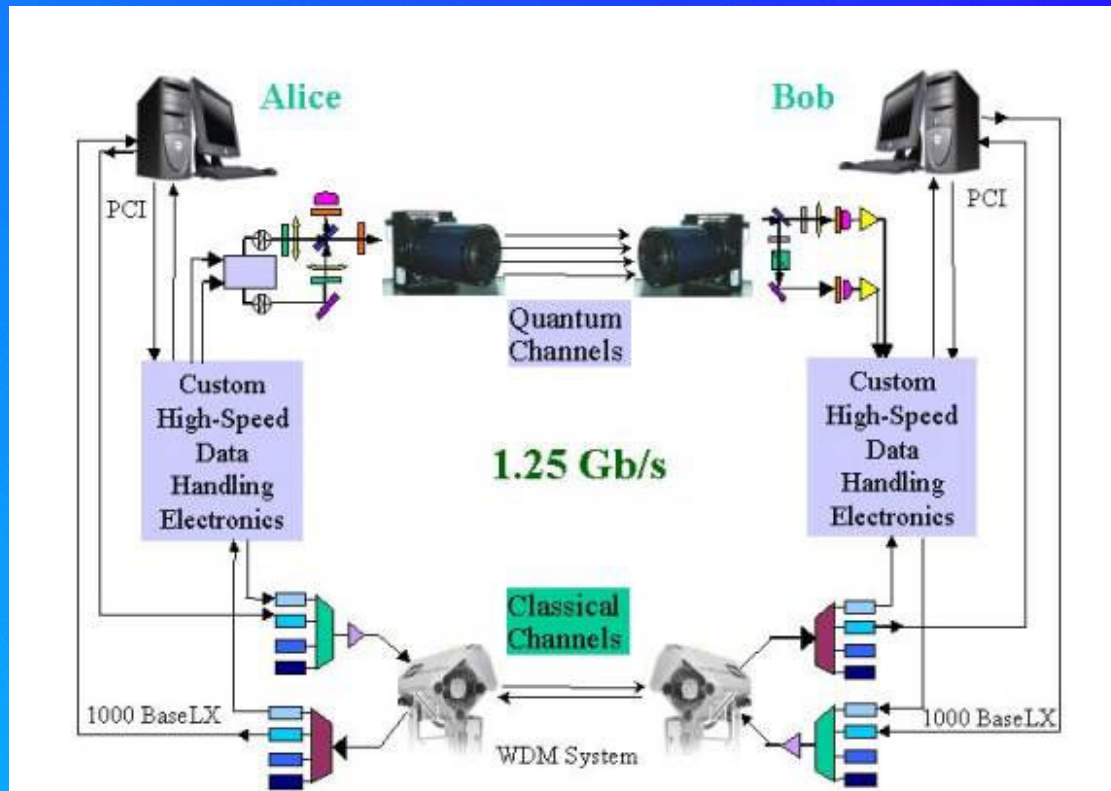
The DARPA Quantum Network



BBN Technologies/Funding by the Defense Advanced Research Projects Agency



NIST Quantum Communication Testbed



PCI interface high-speed electronics boards for Alice (left) and Bob (right).

1 Mbit/s over 4km (2006年)

SECOQC QKD网络拓扑和分布

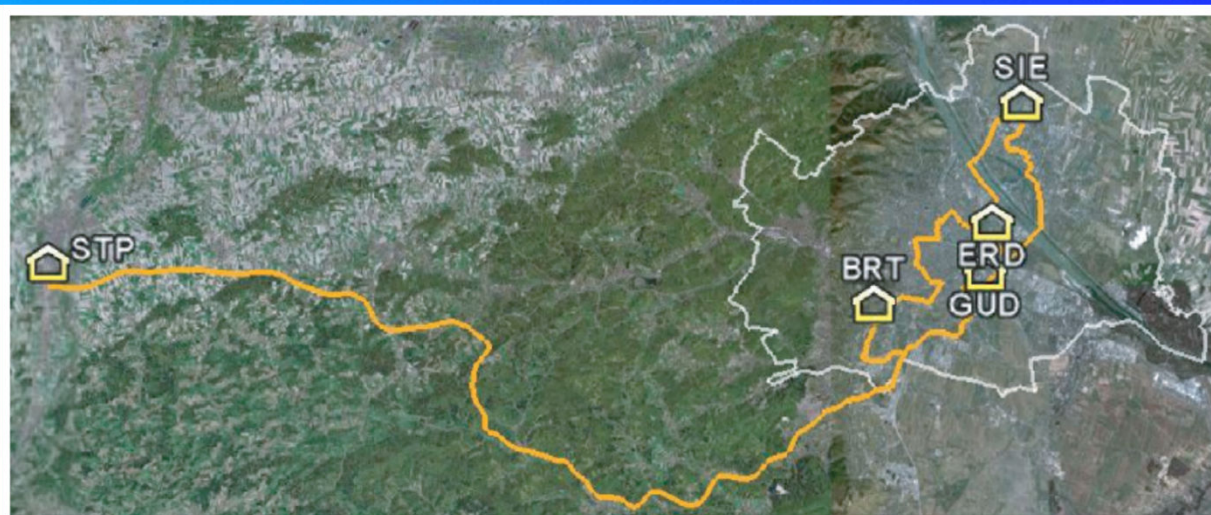
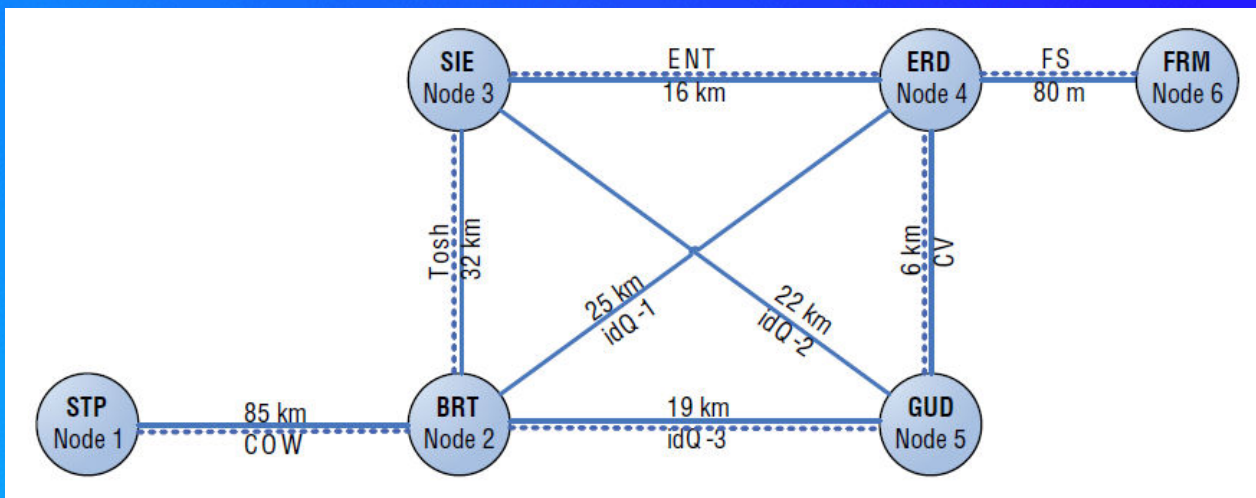


Figure 3. Satellite map with the locations of the nodes of the prototype.

SECOQC QKD节点组成

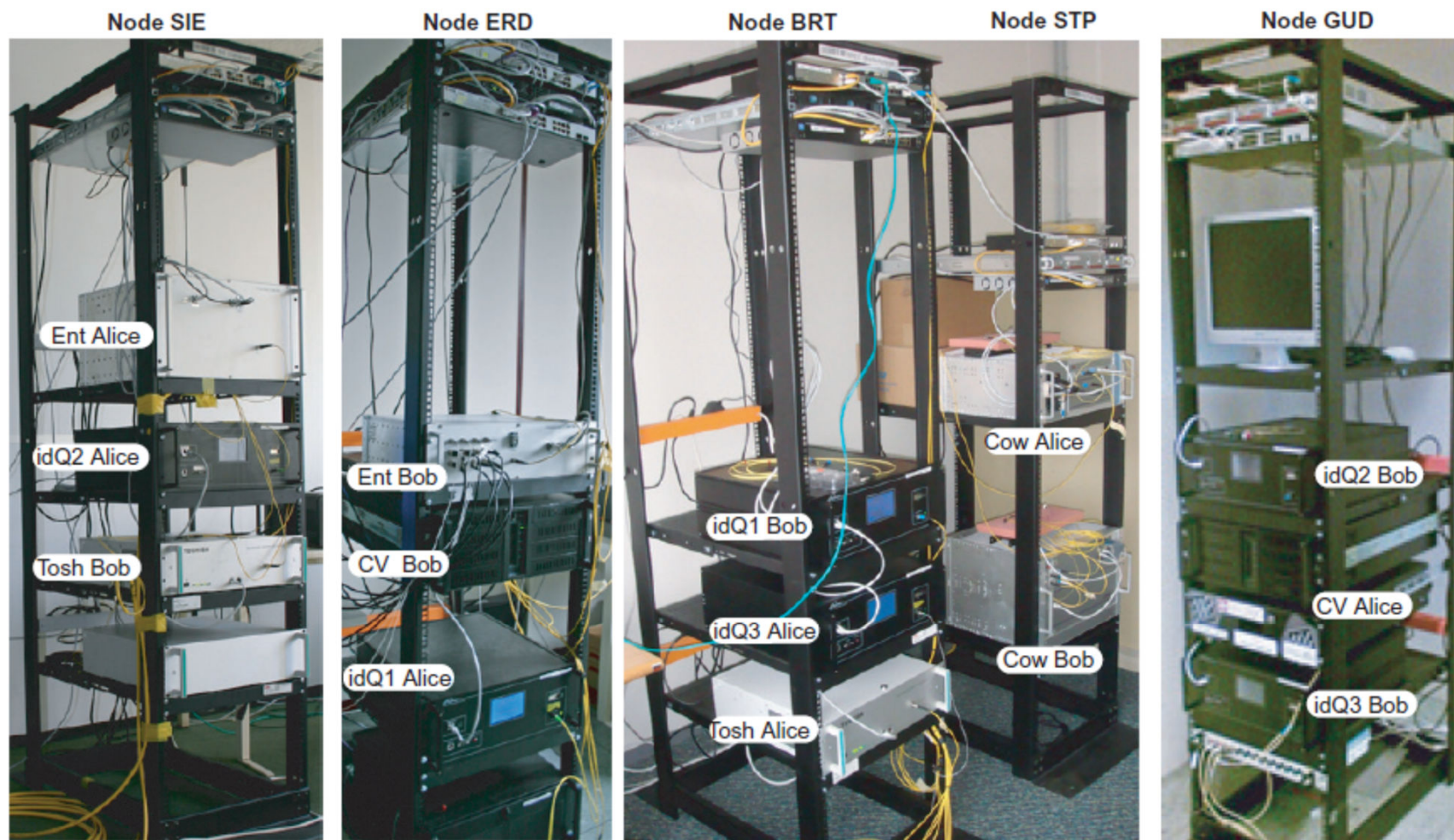


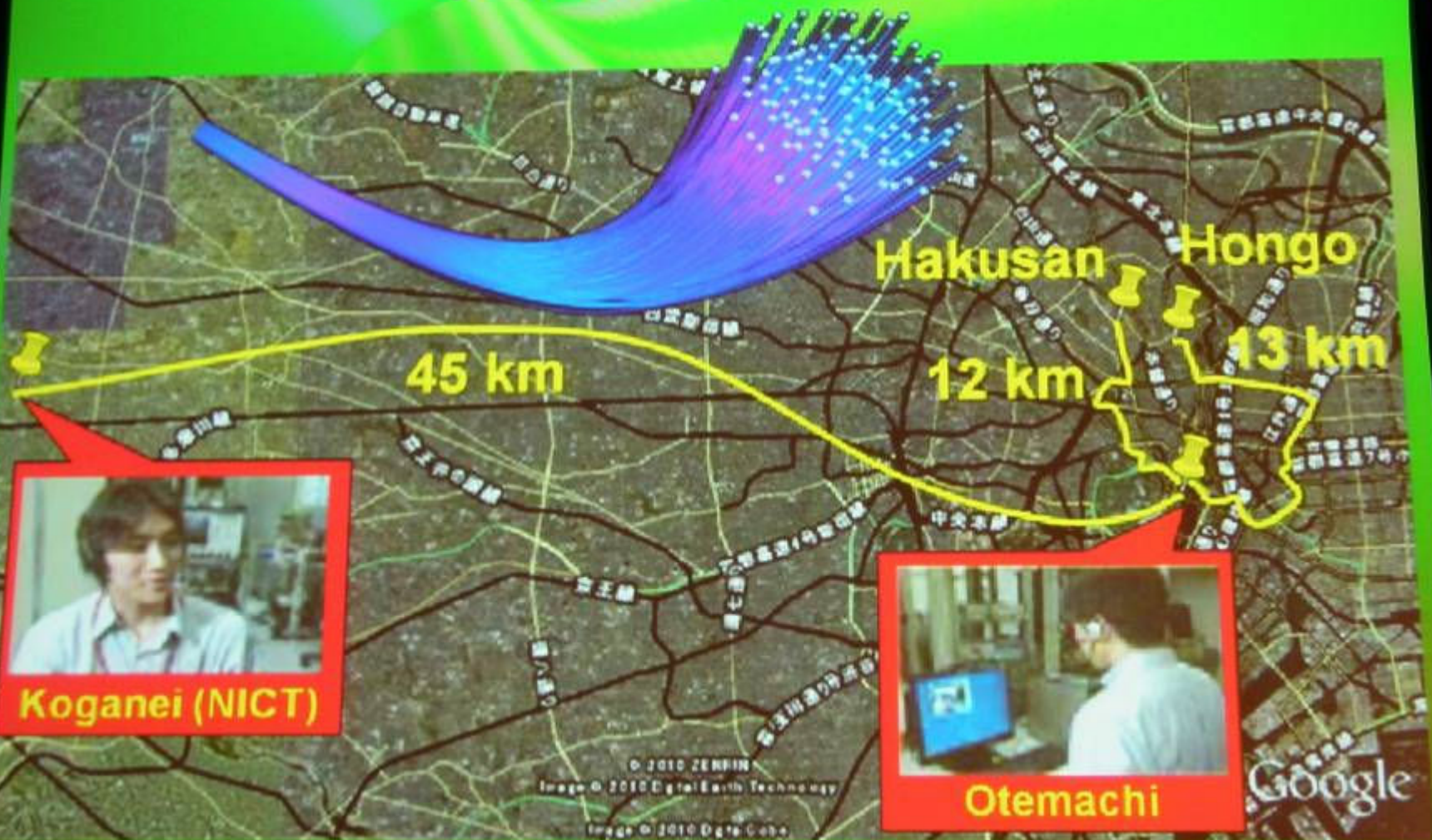
Figure 5. Photographs of the SECOQC network node racks.

成码率: 0.6~10kbps (2008年)

Tokyo QKD network

(2010年)

In the era of the Internet,
the quantum world reaches **city-scale** thanks to
optical fiber networks.





NICT

Empowered by Innovation

NEC

MITSUBISHI

三菱電機

Changes for the Better

 **NTT**



TOSHIBA

Leading Innovation >>>

Toshiba Research
Europe Ltd (TREL)



Id Quantique (IDQ)



Austrian Institute of Technology



Institute of Quantum Optics
and Quantum Information



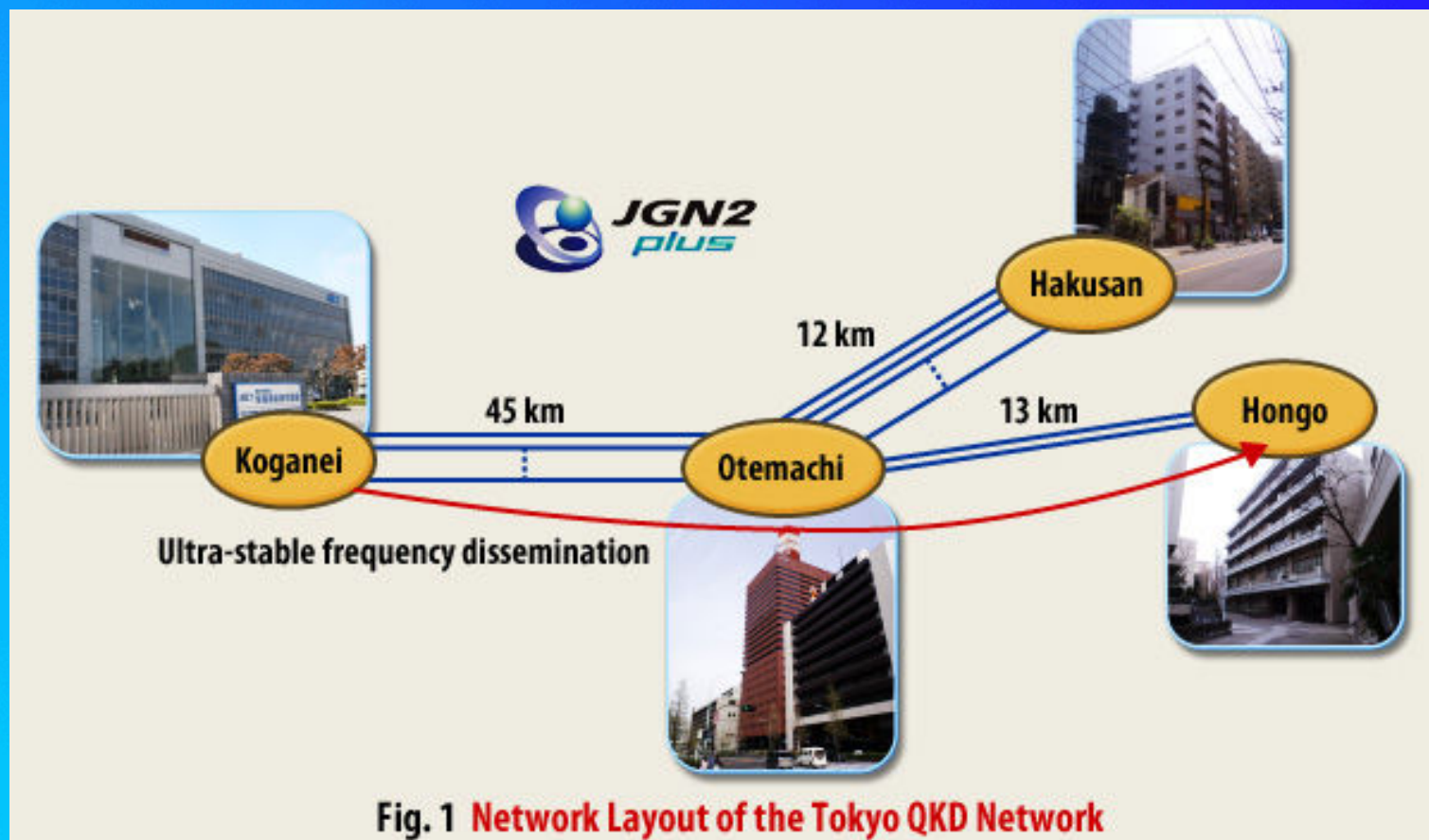
**universität
wien**

University of Vienna

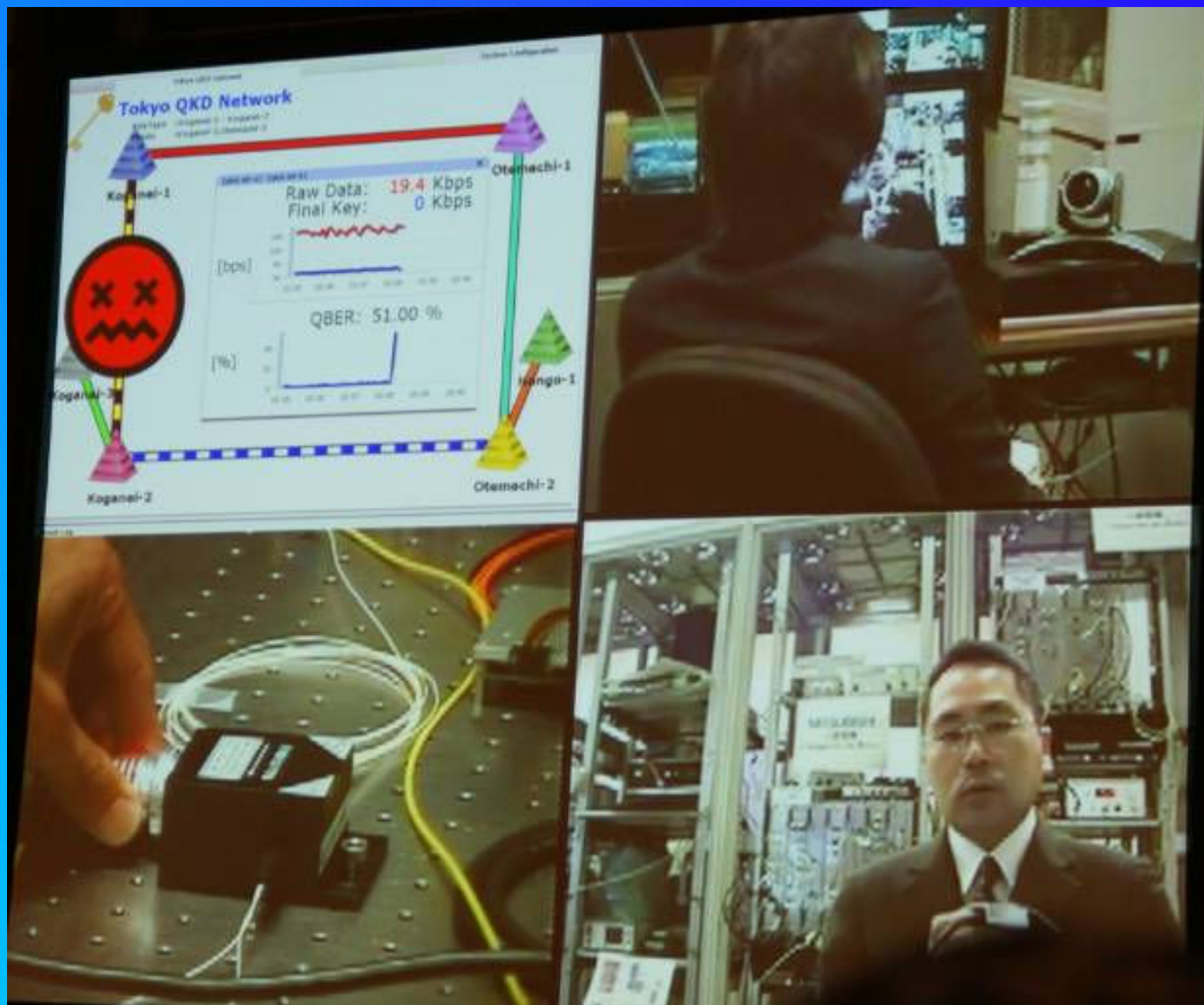
} All Vienna

Tokyo QKD network网络架构

- ◆ 基于JGN2plus (Japan's Gigabit Network)
- ◆ 星形结构



Tokyo QKD Network视频会议演示





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MagiQ QPN™

Ultimate Cryptography Solution for Network Security



Quantum-Safe Network Encryption



Centauris CN9000 Series

- High-assurance, ultra-low latency encryption
- QRNG-powered 100Gbps encryption
- Robust, scalable and simple
- Upgradeable to Quantum-Safe Security



Centauris CN8000

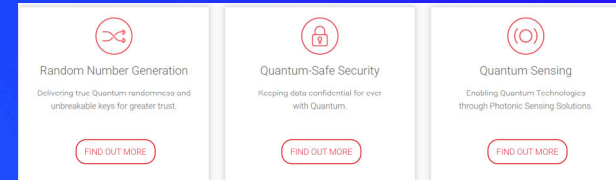
- Uncompromising performance, flexibility and scalability
- QRNG-powered, multi-link encryption
- Multi-tenant, Ethernet & Fibre Channel encryption
- Upgradeable to Quantum-Safe Security

ID Quantique 产品

◆ id Quantique (IDQ) 在2001年建于Geneva

◆ 公司产品

- Centauris Layer 2 Encryptors: High speed multi-protocol encryptors
- Cerberis: A fast and secure solution of high speed encryption combined with quantum key distribution。典型的基于AES应用
- Clavis²: QKD for R&D Applications
- 探测器，随机数发生器，短脉冲激光源等



Quantum-Safe Network Encryption



Centauris CN9000 Series

- High-assurance, ultra-low latency encryption
- QRNG-powered 100Gbps encryption
- Robust, scalable and simple
- Upgradeable to Quantum-Safe Security

[PRODUCT DETAILS](#)



Centauris CN6000 Series

- Robust, business-class encryption
- Addressing the most performance-intensive environments
- Ultra-reliable, defence-grade for enterprise customers
- Upgradeable to Quantum-Safe Security

[PRODUCT DETAILS](#)



Centauris CN4000 Series

- High-assurance, transparent, full-line rate encryption
- Versatile, supports all Layer 2 network topologies
- Cost-effective
- Easy installation and management

[PRODUCT DETAILS](#)



Centauris CV1000 Virtual Encryptor

- Agile, scalable solution
- Multi-Layer (L2, L3 & L4) network architectures
- 100% interoperability with IDQ Centauris encryptors
- Cost-effective

[PRODUCT DETAILS](#)

Quantum Key Distribution



Clavis XG QKD System

- Long range (up to 150 km)
- High key rate (>100 kb/s)
- Complex network topologies (ring, hub and spoke, meshed, star)
- Controlled and monitored centrally
- Interoperability with major Ethernet and OTN encryptors

[PRODUCT DETAILS](#)



Cerberis XG QKD System

- Short/medium range (up to 90km)
- Standard key rate (2kb/s)
- Complex network topologies (ring, hub and spoke, meshed, star)
- Controlled and monitored centrally
- Interoperability with major Ethernet and OTN encryptors

[PRODUCT DETAILS](#)



XGR Series - QKD Platform

- Open QKD platform for R&D applications
- Embedded KMS for key distribution
- Interface to external encryptors
- User-friendly interface for technology evaluation and testing

[PRODUCT DETAILS](#)



Cerberis³ QKD System

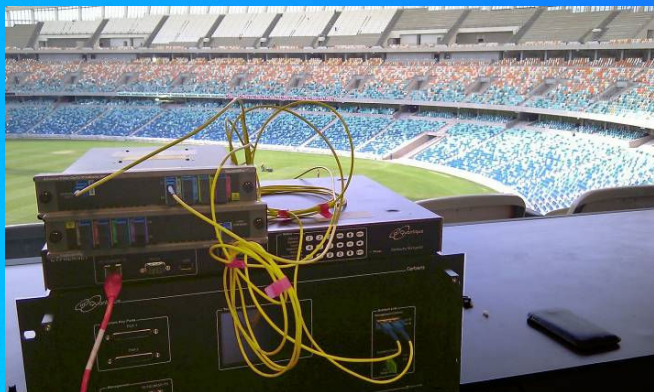
- Complex network topologies (ring, hub and spoke)
- Interoperability with major Ethernet and OTN encryptors
- Easy integration in any data centre
- Centrally monitored solution
- Multiplexing of all channels on single fibre for metropolitan area

[PRODUCT DETAILS](#)

ID Quantique

2010 FIFA 世界杯

Durban, South Africa – The first use of ultra secure quantum encryption at a world public event, 基于AES 256



2019 SK Telecom Continues to Protect its 5G Network with Quantum Cryptography Technologies

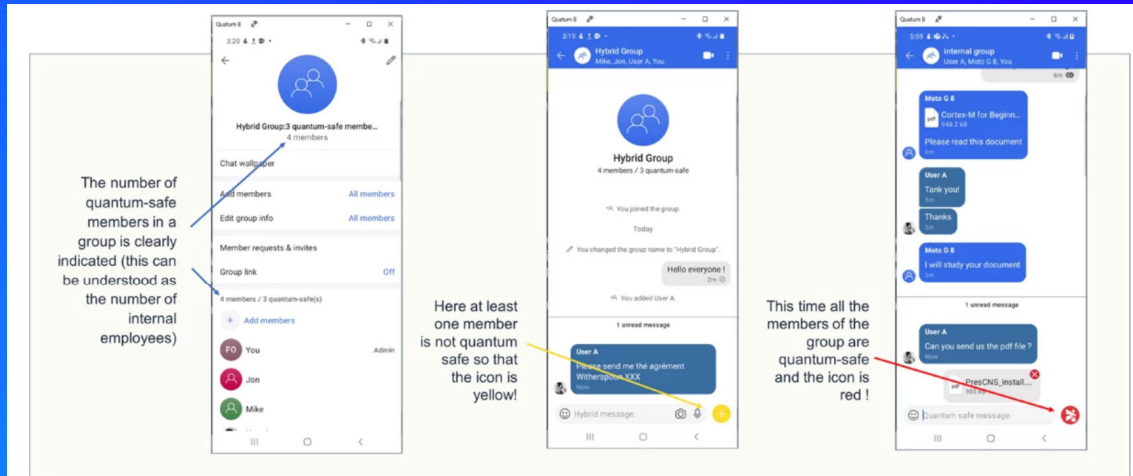


SK Telecom Continues to Protect its 5G Network with Quantum Cryptography Technologies

- SK Telecom applied Quantum Random Number Generator (QRNG) to the subscriber authentication center of its 5G network
- SK Telecom plans to apply Quantum Key Distribution (QKD) technology to the Seoul-Daejeon section of its LTE and 5G networks to prevent hacking and eavesdropping
- SK Telecom is playing a pivotal role in global standardization of QKD and QRNG technologies at ITU-T.

ID Quantique

Quantique and CryptoNext partner to deliver next-gen, quantum-safe messaging



The solution aims at enabling governments, enterprises and organizations of all types to manage sensitive communications for specific groups of people, such as executive teams, and/or specific projects.



Telefonica, Fortinet & IDQ demonstrate the first Quantum-Safe IPVPN connection suitable for managed datacentre interconnect

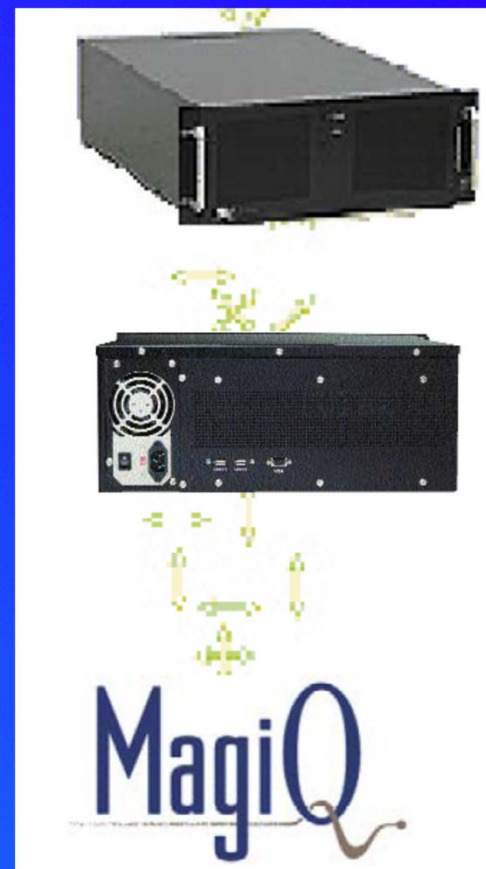
7th October 2021

Telefonica, Fortinet and IDQ have jointly demonstrated the first Quantum-Safe IPVPN connection suitable for offering a fully managed datacenter interconnection service.

[DISCOVER MORE](#)

MagiQ

- ◆ 1999建立于美国，目前设有Boston总部和纽约Office。
- ◆ 大致从2008年起建立了MagiQ Research Labs，与US Army, DARPA, NASA以及与包括世界500强的多个公司进行联合研究。



MAGIQ QPN™ 8505

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Ultimate Cryptography Solution for Network Security

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MAGIQ QPN™

Ultimate Cryptography Solution for Network Security

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MagiQ QPN™: State of the Art Quantum Cryptography

MagiQ QPN is a market leading Quantum Cryptography solution that delivers advanced network security and fool-proof defense against the numerous cryptographic key distribution and management challenges.

Keys generated and disseminated using QPN quantum cryptography consist of truly random characters that are distributed based upon the laws of quantum mechanics, which guarantees that **keys cannot be intercepted during the key exchange session**. Therefore, MagiQ QPN provides security that will remain secure against future advances in algorithms, computational power, hardware design, and even quantum computing.

How it Works

Who Needs It?

Features & Benefits

Protecting **financial information** is one of the highest priorities of corporations and entities involved in financial management and securities exchange. With MagiQ QPN, financial organizations can secure their most critical communication links to prevent intrusion and data theft. MagiQ QPN supports a variety of network architectures and provides the cryptographic key exchange infrastructure to protect the information channels.

Storage area networks offer the promise of protecting corporate assets offsite by creating electronic copies of critical information for future retrieval. Encryption is used to protect the data link to the storage site (data in transit) and to protect the data at the site (data at rest). QPN guarantees high-security in storage area network applications to better meet customer security requirements now and for the future.

Military and Government

Hostile forces are a real and a continuous threat to government and military network security. QPN can safeguard against hackers and unwanted network security breaches by "trusted" insiders attempting to access highly-classified government and military information.

MagiQ QPN enables future-proof quantum security for other industries as well:

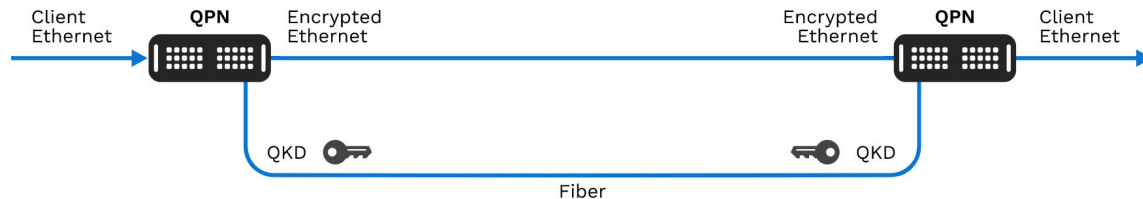
- ✓ R&D companies looking to protect trade secrets, intellectual properties, patents and business plans
- ✓ Voice and data service providers who need to secure confidential customer data and/or access to the network command channel
- ✓ Large Power Grid Providers open to terrorist or malicious hacking into the command and control channel interfaces

How it Works

Who Needs It?

Features & Benefits

The security of quantum cryptography lies in its ability to exchange the encryption keys with absolute security – Quantum Key Distribution. By sending the key bits encoded at the single photon level on a photon-by-photon basis, quantum mechanics guarantees that the act of an eavesdropper observing a photon irretrievably changes the information encoded on that photon. Therefore, the eavesdropper can neither copy nor clone, nor read the information encoded on the photon without modifying it; eavesdropping is instantly detected making this key exchange uncompromisingly secure.



QPN implements the BB84 protocol, invented by Bennet and Brassard in 1984. This protocol assumes that the sender and recipient share an optical link (fiber) and a classical (non-quantum) unsecured communication channel, for example, a standard internet link.

QPN sends photons over the fiber to create the secure keys between two QPN stations. A photon is an elementary light particle that has measurable properties, like polarization, which can be 'up' or 'down'. These can be used to encode and transmit a value of a bit from one QPN station to the other. The transmitting QPN station uses a truly random number generator to come up with the value of the bit encoded on the photon.

The security of the BB84 protocol is based on the fundamental Heisenberg Uncertainty Principle, that states that observing a photon (eavesdropping) does change its properties, i.e., in the presence of eavesdropping, the values of the received bits will differ from the values of the bits sent. This fundamental principal eliminates the ability of any eavesdropper to hide his/her 'footprints' on the photon.

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Quantum Phone Calls

Certain conversations or transactions meant to be private. Yet despite the of digital communication in one fo

knowledge that the message cannot be opened by an eavesdropper, at least not without alerting you to the breach. **Chen et al. demonstrate a quantum key distribution protocol in a real-world application scenario, with the quantum**

computed over a network consisting of ons linked by 20 km of commercial

er. The generated keys can be used tely in the context of encrypted real-telephone conversations between the sep-Sharing quantum mechanically-enarated stations. **With such a demonstration,** photons can provide a secure key v **quantum privacy in your own home may not be** to encrypt and send a message, sa **a too distant prospect.** — ISO

有了这样的演示，量子隐私进入千家万户不会是很遥远的未来。

mechanics closes that loophole. Sharing quantum mechanically-enarated stations. **With such a demonstration,** photons can provide a secure key v **quantum privacy in your own home may not be** to encrypt and send a message, sa **a too distant prospect.** — ISO

physicworld.com

News & Analysis

Applications

China creates quantum network

Researchers in China claim to have built what they say is "the world's first quantum cryptography network for telephony". They have used the network to send completely secure telephone messages between three nodes located in Hefei, Anhui Province, in the east of the country. They say that the new system is better suited to real-world applications than networks developed by rival researchers.

Quantum cryptography exploits the principles of quantum mechanics to create keys for encoding and decoding messages with complete security. These keys are made up of the quantum states of subatomic particles, which means that an eavesdropper who tries to observe the keys will alter them and therefore reveal their presence. Several firms, such as Toshiba and MagiQ Technologies, have built commercial quantum cryptographic devices but usually these are limited to sending encrypted data between two fixed points.

The Chinese network, developed by Jianwei Pan and colleagues at the University of Science and Technology of China, involves three nodes connected in a chain by two 20 km-long commercial fibre-optic cables. Quantum



Coded conversation
The quantum network in Hefei, China, allows secure communication down 20 km fibre-optic cables.

keys consisting of photons with varying phase are shared between the adjacent nodes. Pan and colleagues claim to have used their network to send telephone messages in real time between three users as well as broadcast voice messages from one user to the other two (*Optics Express* 17 6540). According to Pan's colleague Zeng-Bing Chen, the network has a number of advantages over quantum-cryptographic networks built in other countries because it uses "decoy" photon pulses. He points out that not only do the decoy pulses make the network more secure – by preventing eavesdroppers siphoning off the excess pho-

tons generated by imperfect single-photon sources – but they also allow faster key generation and offer potentially longer distances between nodes – up to some 100 km, compared with 30 km for rival technologies. In addition, he says that the equipment used at each node is compact, cheap – costing about €50,000 – and reliable.

However, Christian Momyk, project manager of the European-Union funded Secure Communication based on Quantum Cryptography consortium, which displayed a six-node quantum-cryptography network in Vienna last year (see *Physics World* November 2008 p10), believes the Chinese set-up is not really a network because messages cannot be rerouted if faults occur. He also says that quantum key distribution in the Chinese network is integrated into the telephony applications and so other kinds of secure data transmission – such as document exchange – would require the development of new apparatus, whereas key exchange in the Austrian network is application independent.

Chen says that quantum-key exchange and applications are in fact completely independent in his group's network. He believes that the technology could be used commercially within two or three years, but that the size of the market will depend on further increasing key-generation speeds and extending the maximum distance between links.

Edwin Cartledge

Physics World 的报道

T.-Y. Chen et al., *Optics Express* Vol. 17, Iss. 8, pp. 6540–6549 (2009).

Science 的报道

5节点星型量子密钥分配网络系统

全通型量子通信网络



Chen *et al.*, Optics Express 18, 27217 (2010)

系统集成



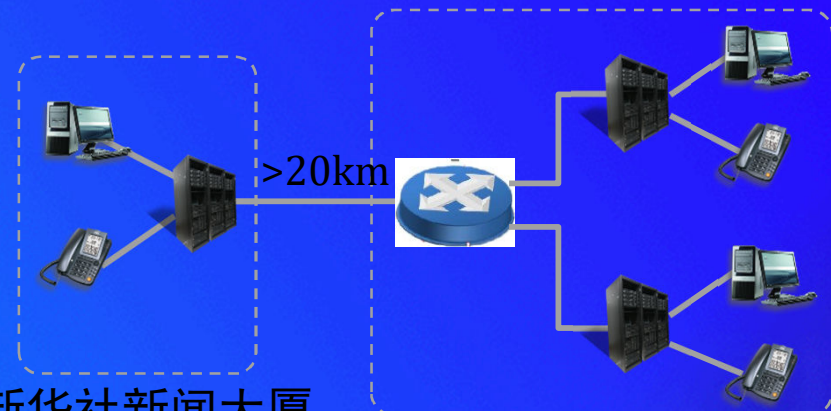
实用化城域量子通信网络



合肥全通型城域量子通信网络

Chen *et al.*, Opt. Express 17, 6540 (2009)

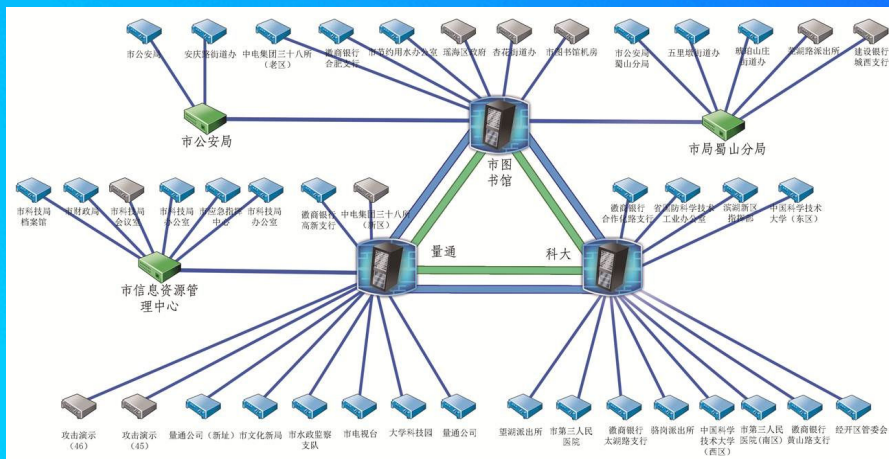
Chen *et al.*, Opt. Express 18, 27217 (2010)



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金融信息量子通信验证网(2012)



合肥城域量子通信试验示范网 (46个节点, 2012年)

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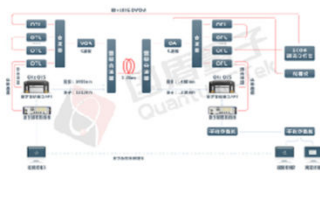
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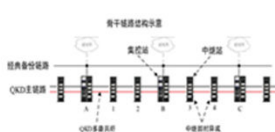
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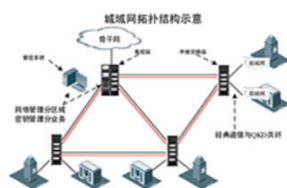
工商银行异地数据千公里级量子加密传输应用



骨干网应用



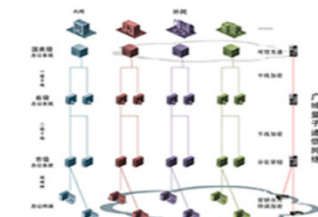
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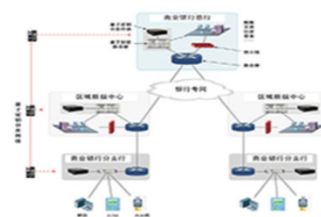
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- 量子密钥高安全保护
- 自主安全操作系统
- 防盗无隐患
- 方便易用
- 5G先锋
- AI智能系统引擎

典型应用

- 移动通话
- 移动办公/作业
- 移动电子政务
- 物联网
- 移动支付

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阿里云、科大国盾量子合作实现
首个云上量子加密通信服务



阿里云

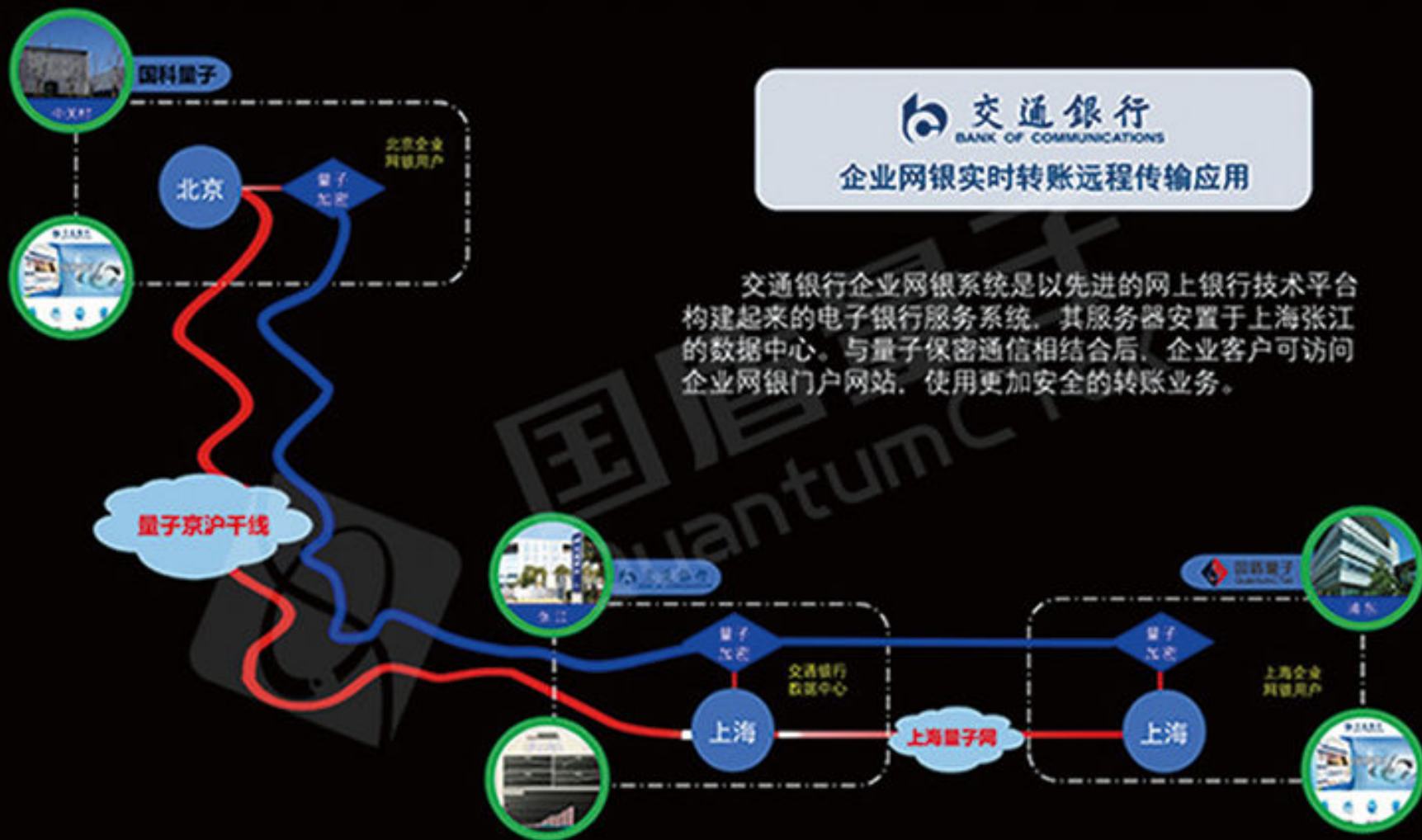


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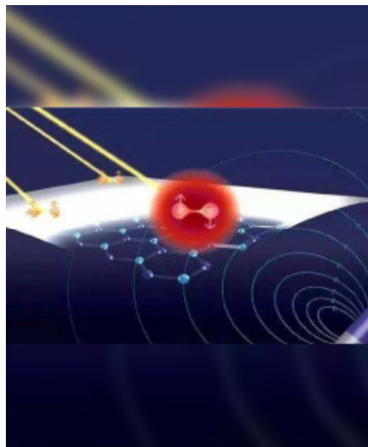


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量子算法利用量子力学许多基本特性，如相干叠加性、并行性、纠缠性、测量坍缩等等，这些纯物理性质为计算效率的提高带来极大帮助，形成一种崭新的计算模式——量子算法。利用NV色心体系，演示了D-J算法，大数分解算法等，向实现室温量子计算机迈出了重要一步。

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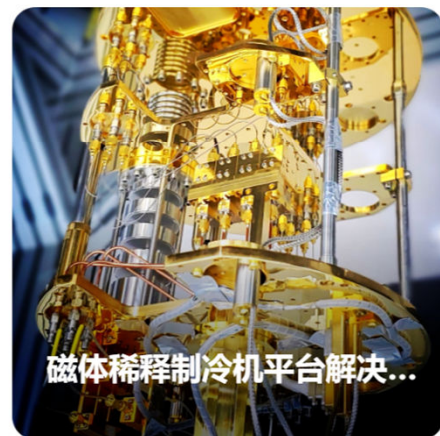
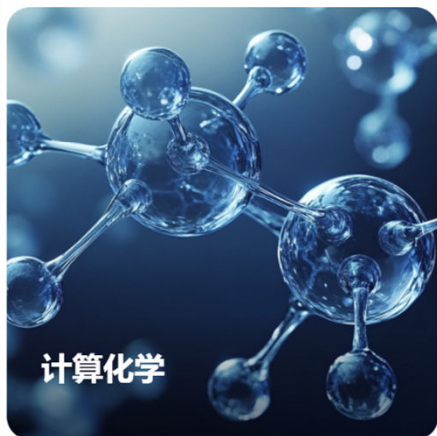
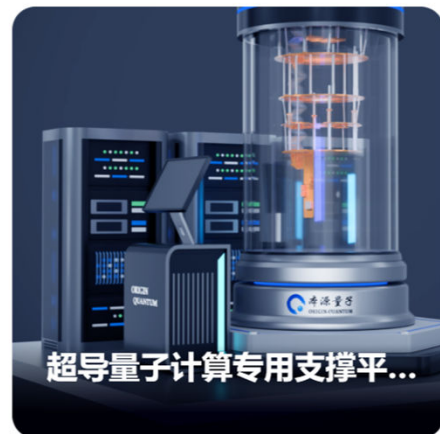
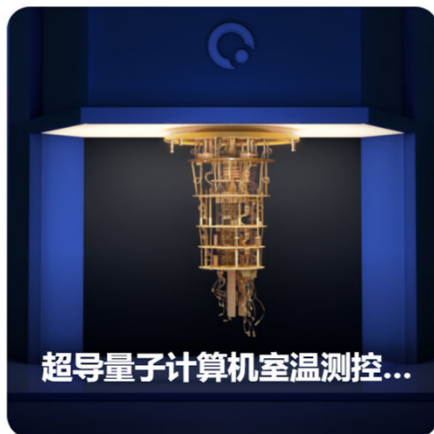
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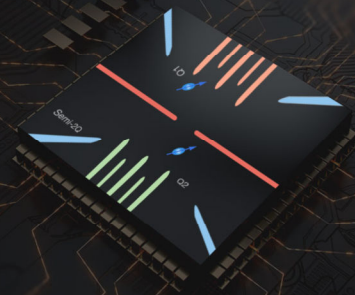


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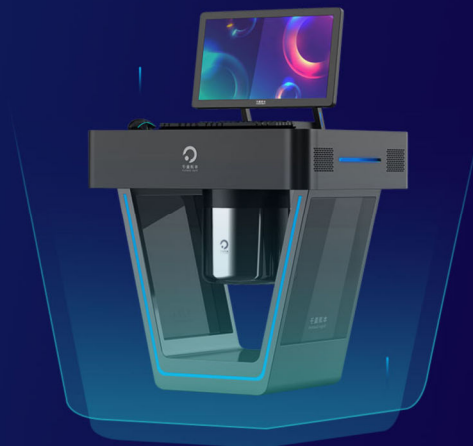
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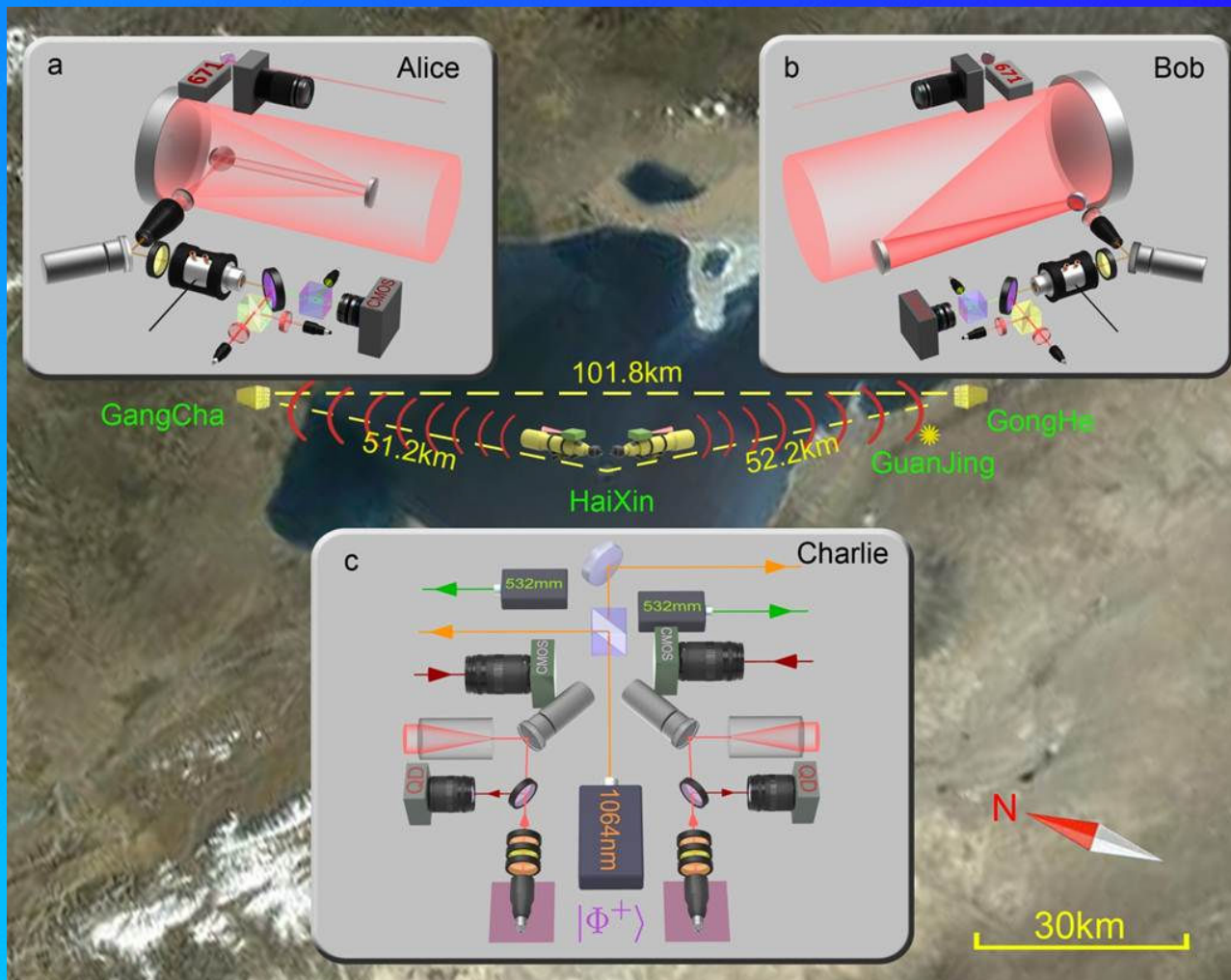
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Free-Space Quantum Communication

Free-space quantum entanglement distribution (over 100km)

Yin et al., **Nature** 488, 185 (2012)



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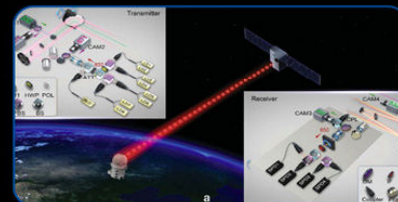
千公里级星地双向量子纠缠分发及
空间尺度量子力学非定域性检验

01



1200公里星地量子密钥分发

02



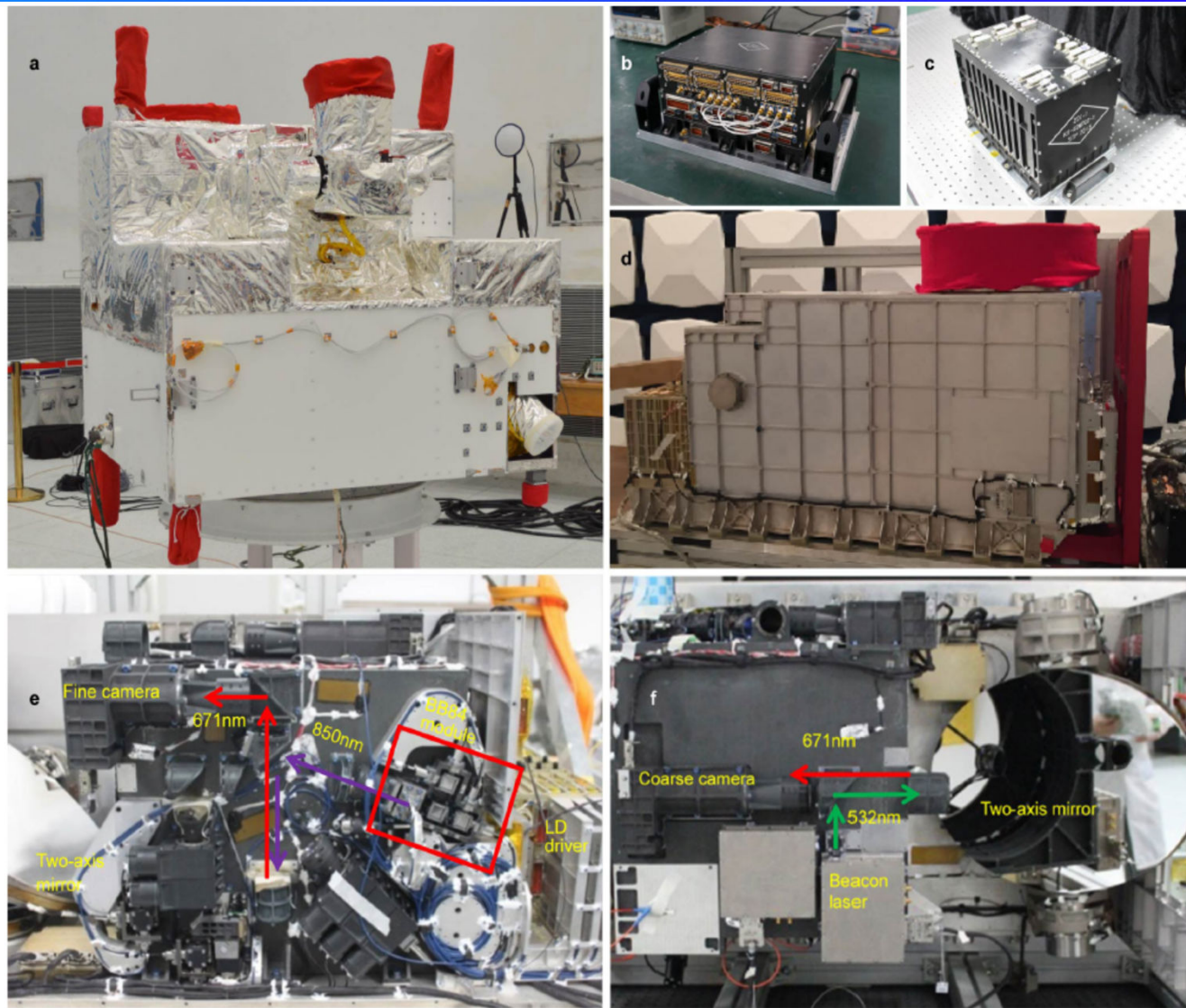
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03



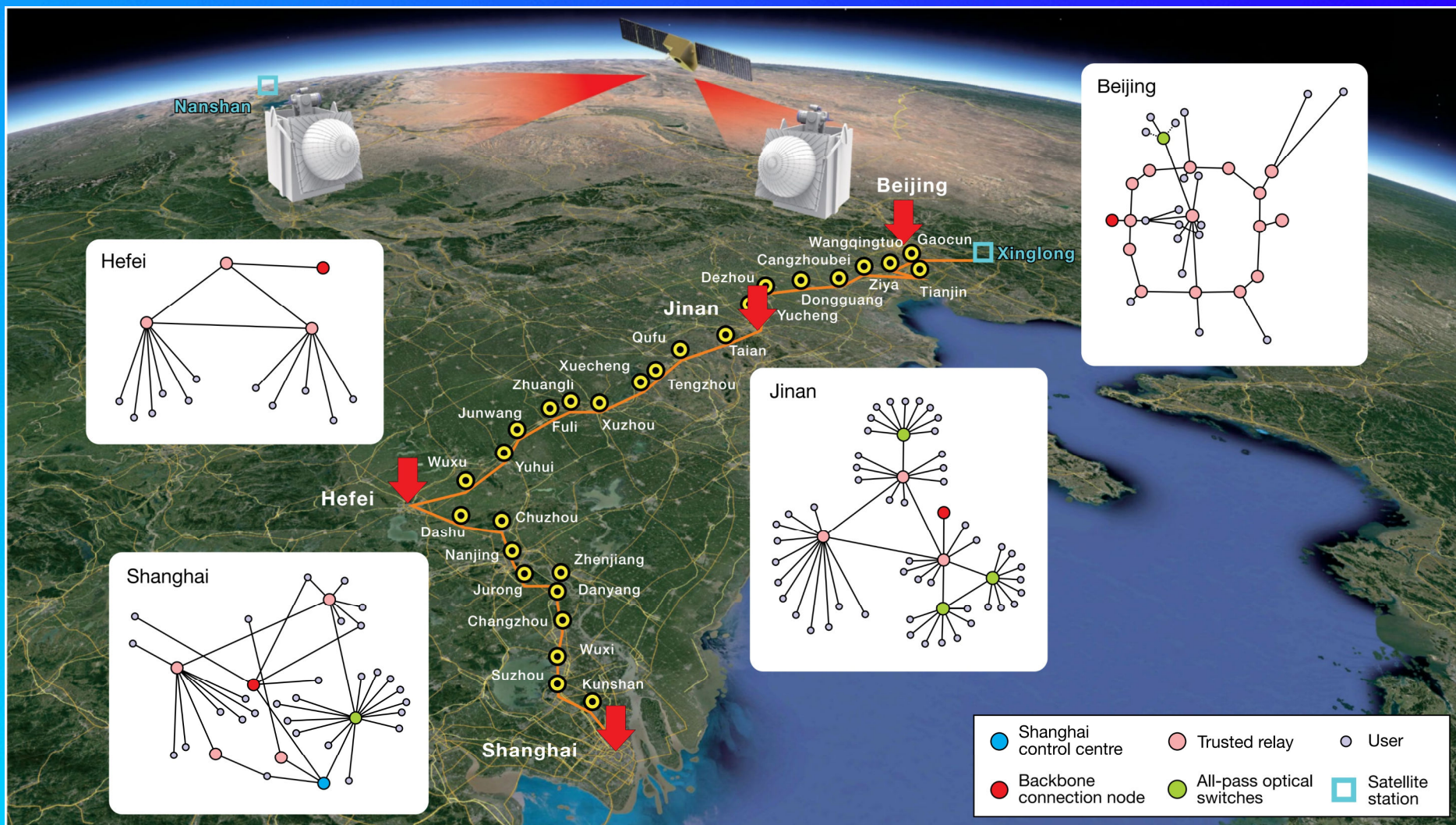
摘自国盾量子新闻

“墨子号”量子卫星与地面站装置图



Extended Data Figure 2 | The Micius satellite and the payloads. a, A full view of the Micius satellite before being assembled into the rocket. b, The experimental control box. c, The APT control box. d, The optical transmitter. e, Left side view of the optical transmitter optics head. f, Top side view of the optical transmitter optics head.

跨越4600公里的天地一体化量子通信网络



Y.A. Chen *et al.*, Nature 589, 214-219 (2021)

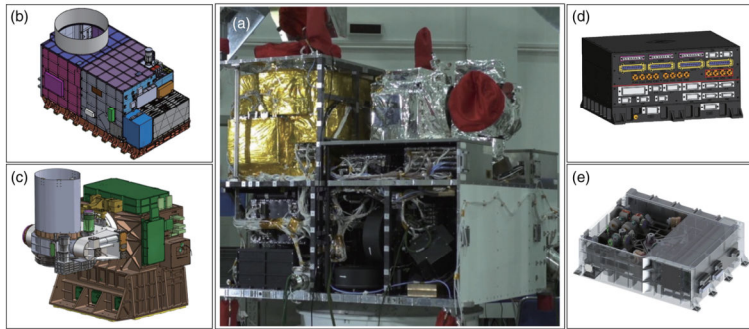


FIG. 18. Full view of the Micius satellite and the main payloads. (a) Photograph of the Micius satellite prior to launch. (b) Transmitter 1 for QKD, entanglement distribution, and teleportation. (c) Transmitter 2, especially designed for entanglement distribution. (d) Experimental control box. (e) Entangled-photon source.

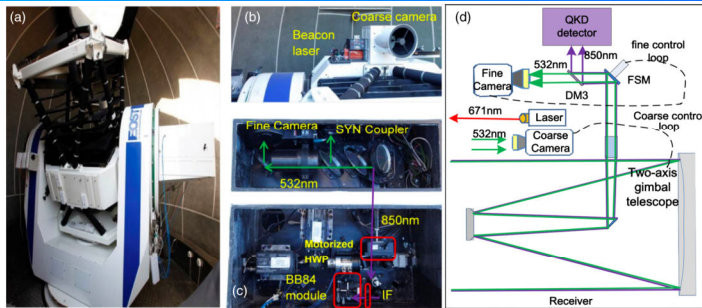


FIG. 23. Typical receiving ground station for the Micius satellite. (a) Two-axis gimbal telescope. (b) Beacon laser and coarse camera. (c) One of the two layers of the optical receiver box. (d) Typical optical design of the receiver including the receiving telescope, the ATP system, and the QKD-detection module. From Liao *et al.*, 2017a.

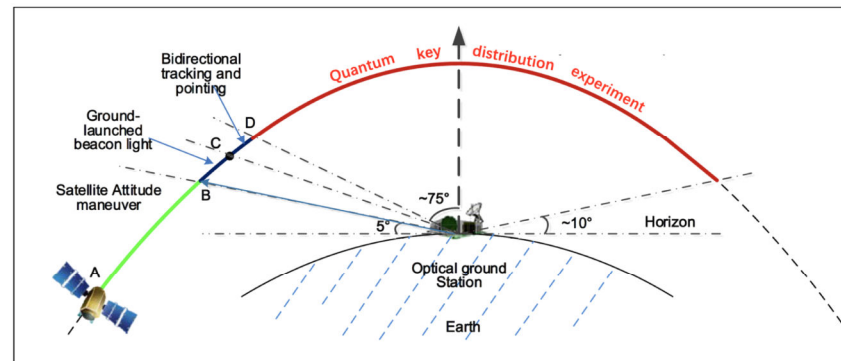


FIG. 27. Tracking and QKD processes during an orbit. From Liao *et al.*, 2017a.

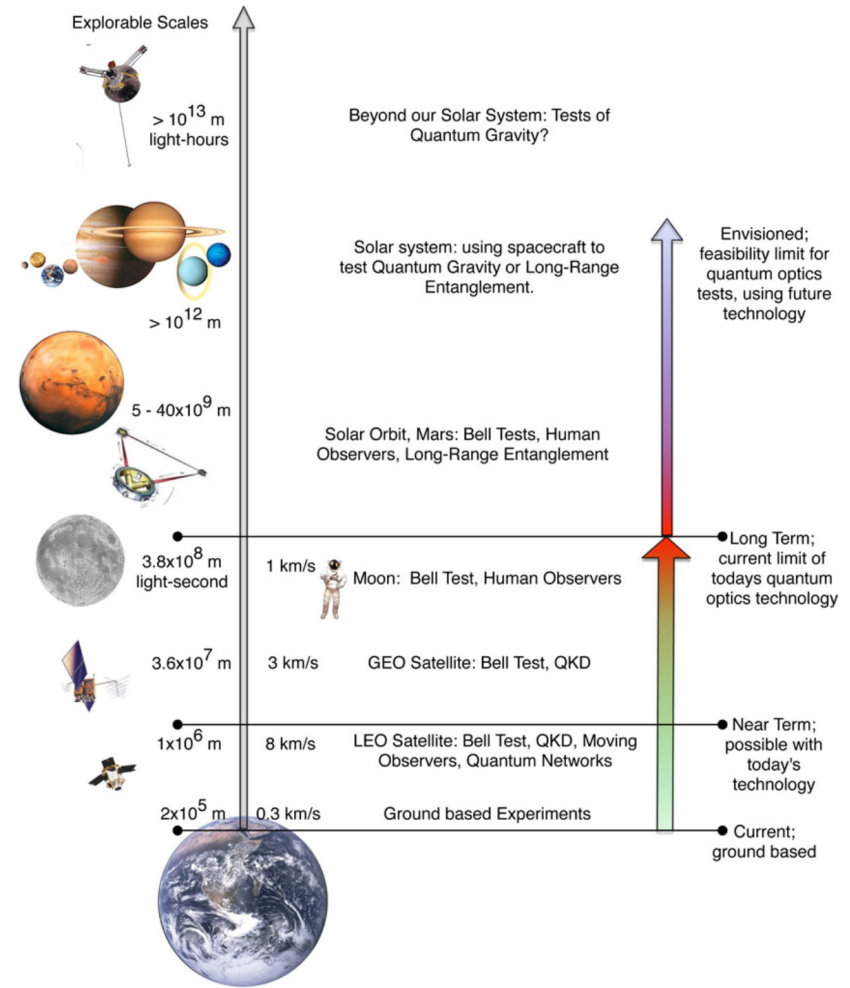


Figure 1. Overview of the distance and velocity scales achievable in a space environment explorable with man-made systems, with some possible quantum optics experiments at each given distance.

美国量子信息国家战略

——以LANL为例

The Quantum Institute at Los Alamos National Laboratory

- ◆ 鼓励交叉研究
- ◆ 理论与实验相结合

... the development of a fully operational quantum computer would demolish the concept of national security. Whichever country gets there first will have the ability to eavesdrop on the plans of its enemies. Although still in its infancy, quantum computing presents a potential threat to global security.

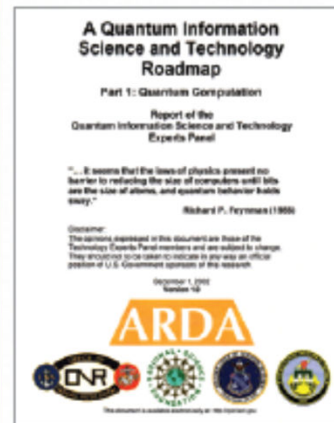
Simon Singh, *The Code Book*



Advanced computing



Manhattan Project



Leading the international effort to plan the future of quantum information science.



Cold-war deterrence

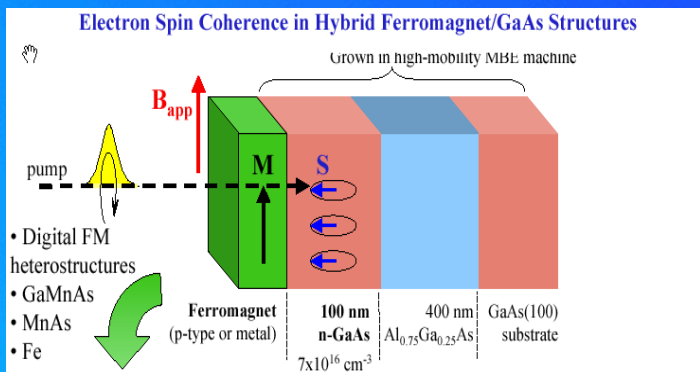


Non-proliferation space technology

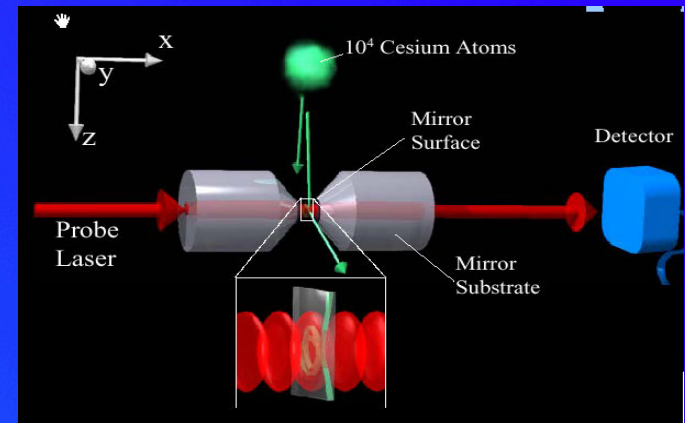
量子信息处理的物理实现

- **Liquid-state NMR**
- **NMR spin lattices**
- **Linear ion-trap spectroscopy**
- **Neutral-atom optical lattices**
- **Cavity QED + atoms**
- **Linear optics with single photons**
- **Nitrogen vacancies in diamond**
- **Electrons on liquid He**
- **Small Josephson junctions**
 - “charge” qubits
 - “flux” qubits
- **Spin spectroscopies, impurities in semiconductors**
- **Coupled quantum dots**
 - Qubits: spin, charge, excitons
 - Exchange coupled, cavity coupled

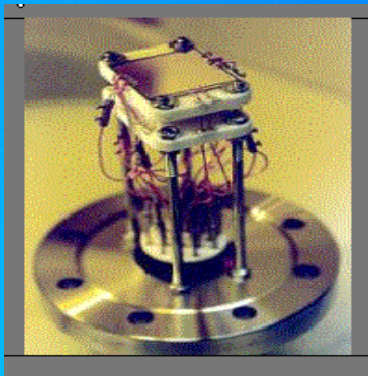




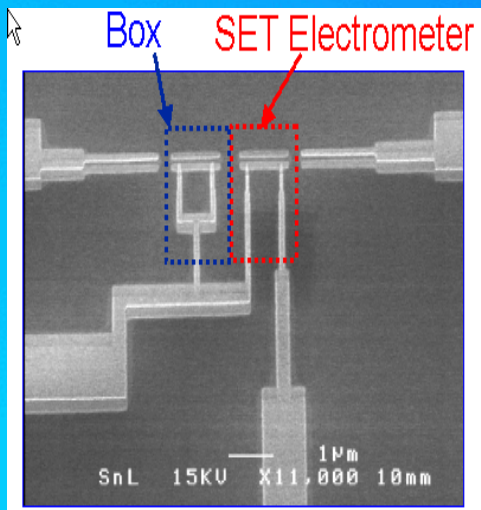
Spintronics



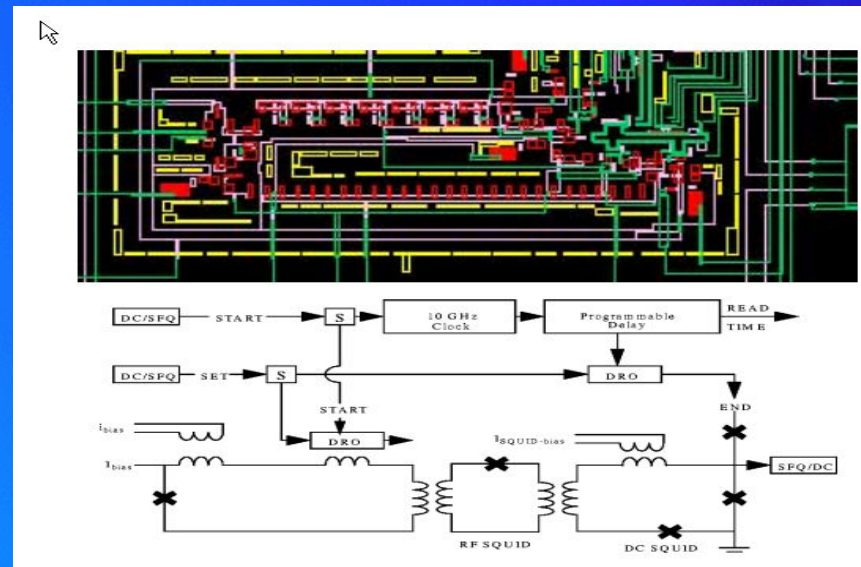
Cavity QED



Atom Chip



Cooper Pair Box



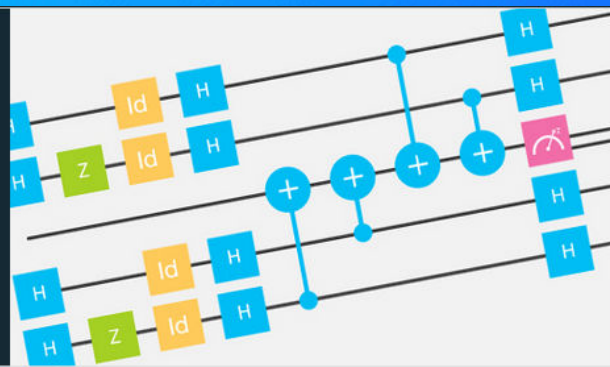
RF-SQUID

量子信息，谁在做？

- Aarhus
- Berkeley
- Caltech
- Cambridge
- College Park
- Delft
- DERA (U.K.)
- École normale supérieure
- Geneva
- HP Labs (Palo Alto and Bristol)
- Hitachi
- id Quantique
- IBM Research (Yorktown Heights and Palo Alto)
- Innsbruck
- Los Alamos National Labs
- McMaster
- MagiQ
- Max Planck Institute-Munich
- Melbourne
- MIT
- NEC
- New South Wales
- NIST
- NRC
- Orsay
- Oxford
- Paris
- Queensland
- Santa Barbara
- Stanford
- Toronto
- USTC
- Vienna
- Waterloo
- Yale
- many others...



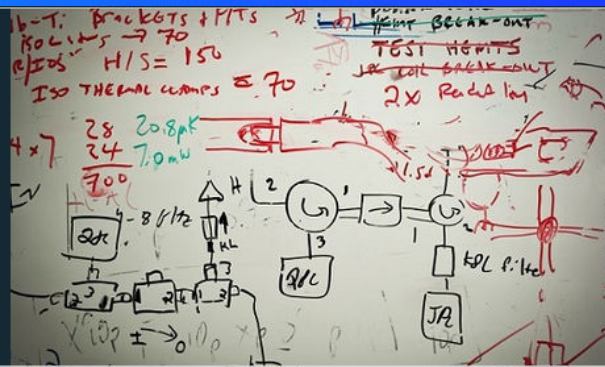
量子计算



Demo: IBM Quantum Experience

Watch a demo of how to use the world's first quantum computing platform delivered via the IBM Cloud.

 Watch the video



Quantum Computing on the Cloud

Hear from IBM experts about the new cloud-enabled quantum computing platform.

 Watch the video

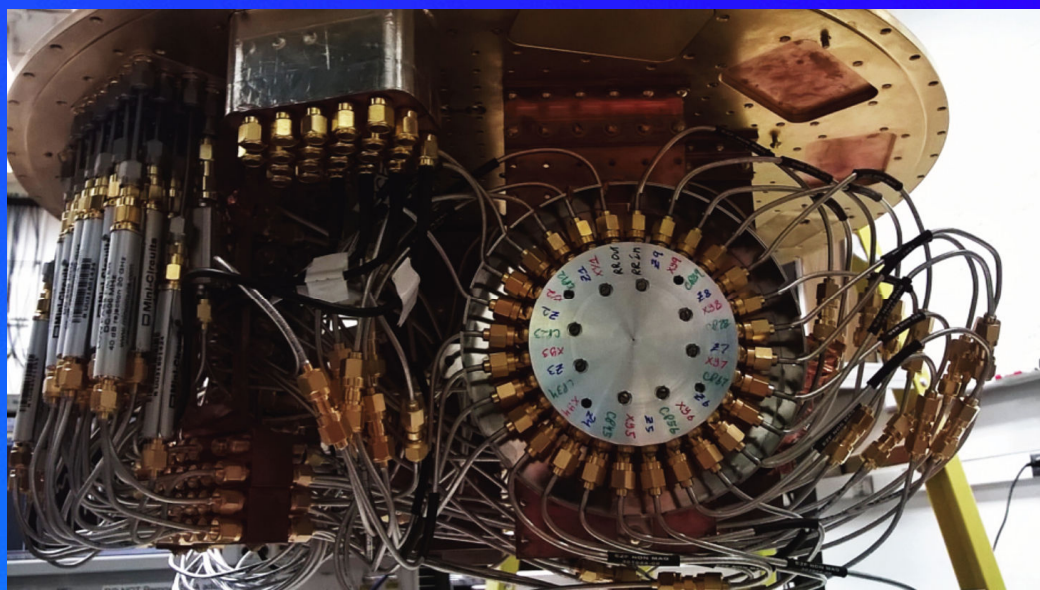
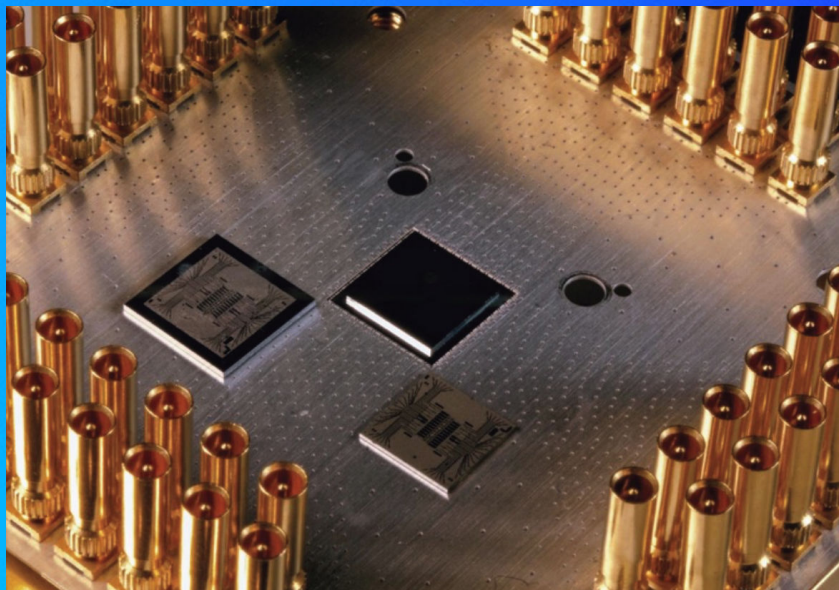


IBM Quantum Computing Lab Tour

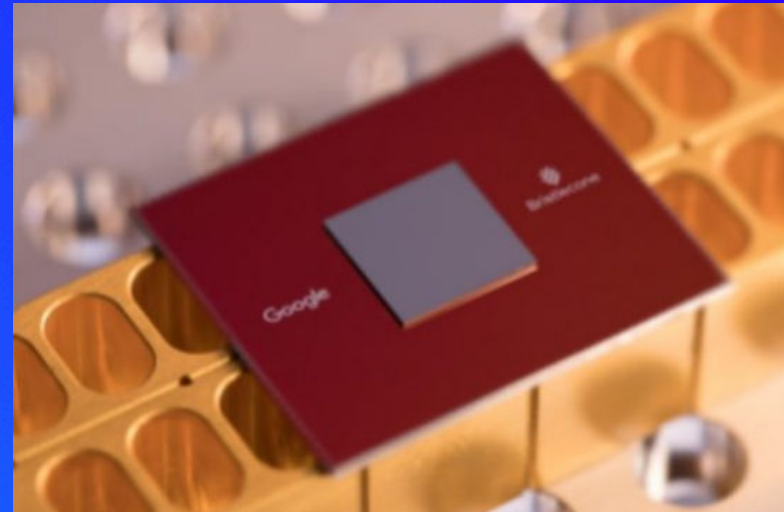
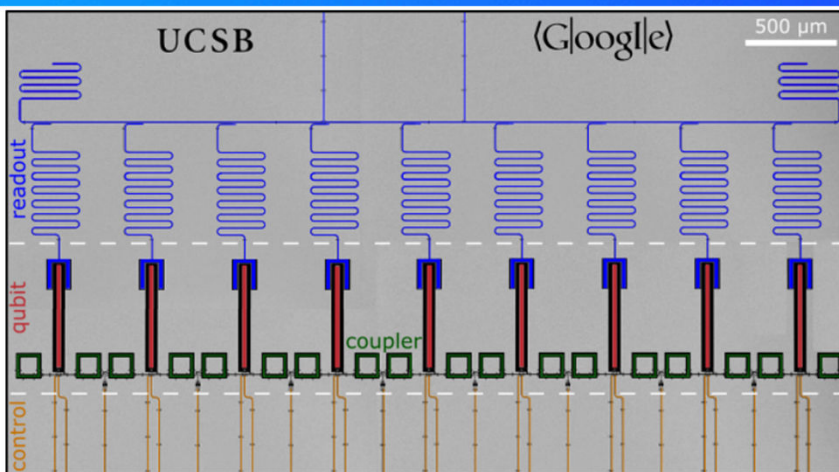
Explore a 360 degree look at the IBM Quantum Computing Lab at the Thomas J Watson Research Center.

 Watch the video

Google量子计算



Google量子计算

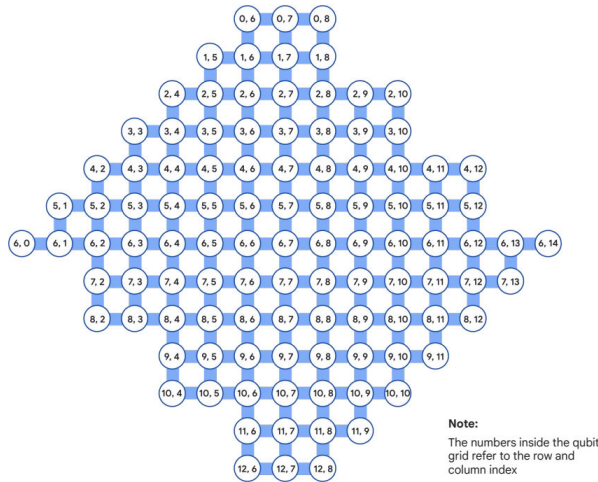


Willow Chip

Number of qubits: 105
Average connectivity: 3.47

Specifications	Quantum Error Correction (QEC, chip 1)	Random Circuit Sampling (RCS, chip 2)
Single-qubit gate error (mean, simultaneous)	0.035%	0.036%
Two-qubit gate error (mean, simultaneous)	0.33% (CZ)	0.14% (iswap-like)
Measurement error (mean, simultaneous)	0.77% (repetitive, measure qubits)	0.67% (terminal, all qubits)
T_1 time (mean)	68 μ s	98 μ s
Measurement rate (per second)	909,000 (surface code cycle = 1.1 μ s)	63,000
Application performance	$\Lambda_{3,5,7} = 2.14$	XEB fidelity depth 40 = 0.1%





Quantum error correction below the surface code threshold

Google Quantum AI

Nature volume 638, 920–926 (2025)

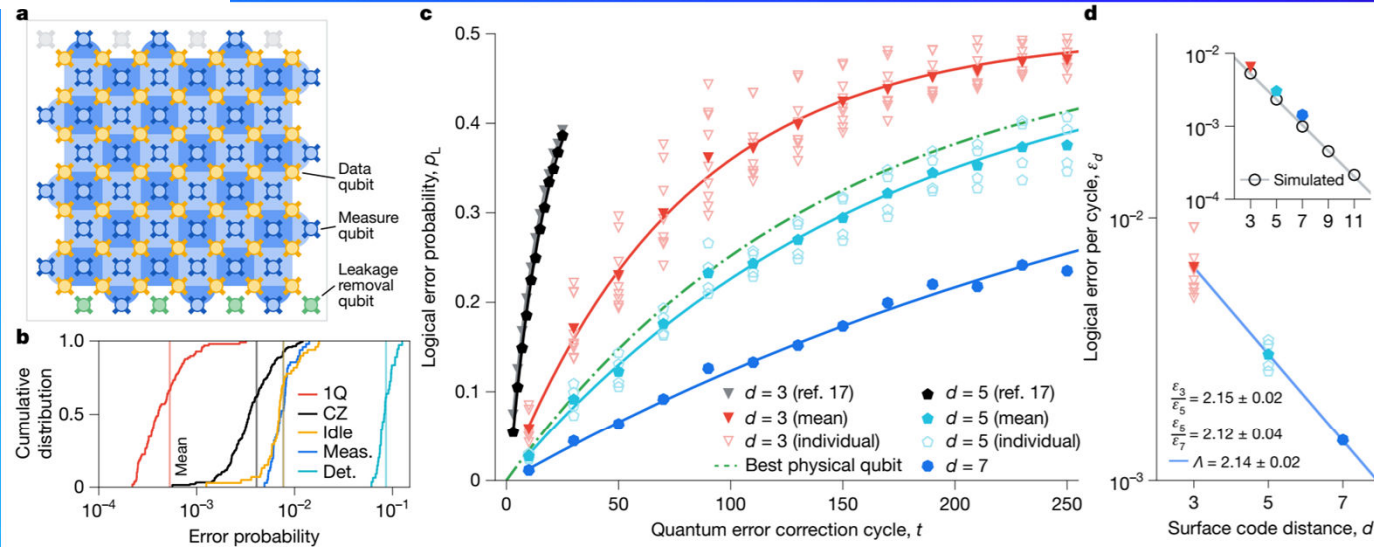


Fig. 1 | Surface code performance. **a**, Schematic of a distance-7 ($d=7$) surface code on a 105-qubit processor. Each measure qubit (blue) is associated with a stabilizer (blue-coloured tile). Data qubits (gold) form a $d \times d$ array. We remove leakage from each data qubit using a neighbouring qubit below it, with additional leakage removal qubits at the boundary (green). **b**, Cumulative distributions of error probabilities measured on the 105-qubit processor. Red, Pauli errors for single-qubit gates; black, Pauli errors for CZ gates; gold, Pauli errors for data qubit idle during measurement and reset; blue, identification error for measurement; teal, weight-4 detection probabilities (distance 7, averaged for 250 cycles). **c**, Logical error probability p_L for a range of memory experiment durations. Each data point represents 10^5 repetitions decoded with the neural

network and is averaged over the logical basis (X_L and Z_L). Black and grey, data from ref. 17 for comparison. Curves, exponential fits after averaging p_L over code and basis. To compute ϵ_d values, we fit each individual code and basis separately and report their average (Supplementary Information). **d**, Logical error per cycle, ϵ_d , reducing with surface code distance d . Uncertainty on each point is less than 7×10^{-5} . The symbols match those in c. Means for $d=3$ and $d=5$ are computed from the separate ϵ_d fits for each code and basis. Line, fit to equation (1), determining Λ . The inset shows simulations up to $d=11$ alongside experimental points, both decoded with ensemble matching synthesis for comparison. Line, fit to simulation; $\Lambda_{\text{sim}} = 2.25 \pm 0.02$.

Our quantum computing roadmap

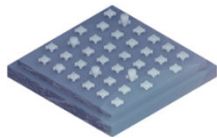
Our focus is to unlock the full potential of quantum computing by developing a large-scale computer capable of complex, error-corrected computations. We're guided by a roadmap featuring six milestones that will lead us toward top-quality quantum computing hardware and software for meaningful applications.



MILESTONE 1

BEYOND CLASSICAL

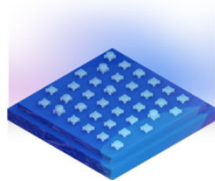
Physical Qubits: 54
Logical Qubit Error Rate: ~



MILESTONE 2

QUANTUM ERROR CORRECTION

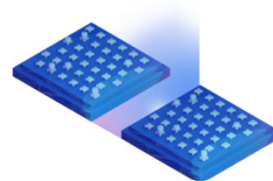
Physical Qubits: 10^2
Logical Qubit Error Rate: 10^{-2}



MILESTONE 3

BUILDING A LONG-LIVED LOGICAL QUBIT

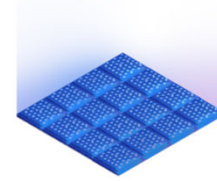
Physical Qubits: 10^3
Logical Qubit Error Rate: 10^{-6}



MILESTONE 4

CREATING A LOGICAL GATE

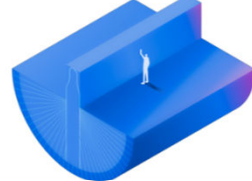
Physical Qubits: 10^4
Logical Qubit Error Rate: 10^{-6}



MILESTONE 5

ENGINEERING SCALE UP

Physical Qubits: 10^5
Logical Qubit Error Rate: 10^{-6}



MILESTONE 6

LARGE ERROR-CORRECTED QUANTUM COMPUTER

Physical Qubits: 10^6
Logical Qubit Error Rate: 10^{-13}

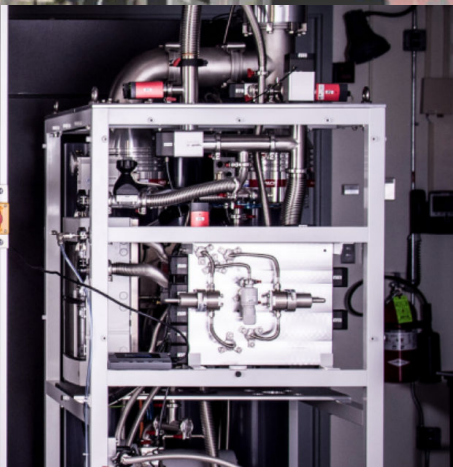
2019

2023

IBM量子计算



Quantum Starts Here



IBM量子计算

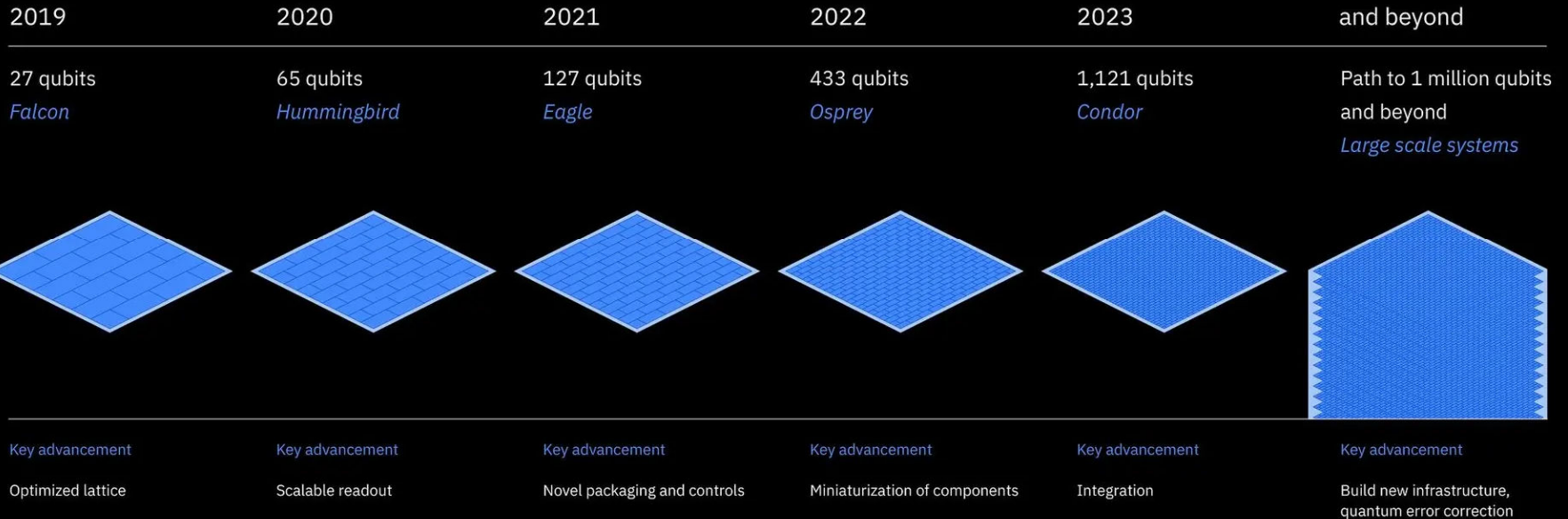
Scaling IBM Quantum technology



IBM Q System One (Released)

(In development)

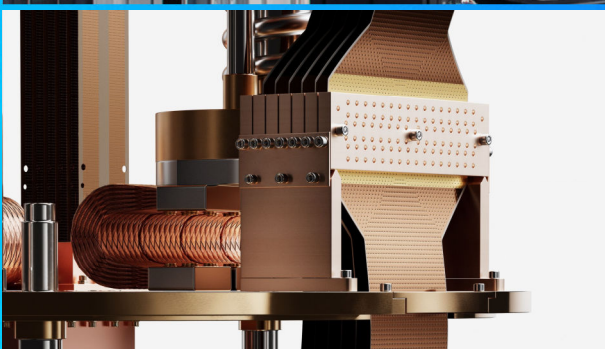
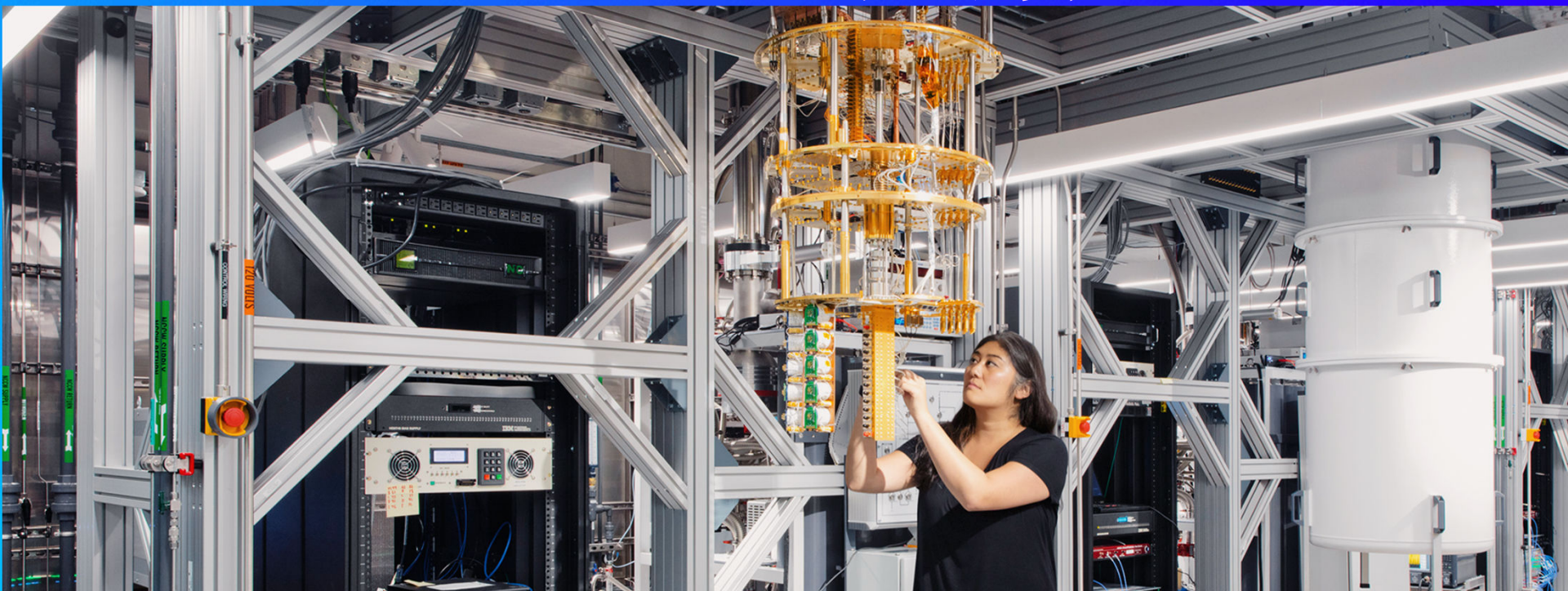
Next family of IBM Quantum systems



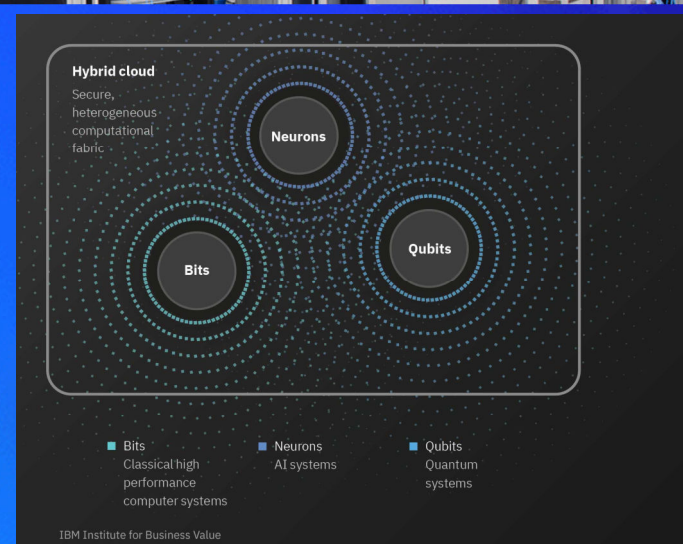
A look at IBM's roadmap to advance quantum computers from today's noisy, small-scale devices to larger, more advance quantum systems of the future. Credit: StoryTK for IBM

<https://www.ibm.com/blogs/research/2020/09/ibm-quantum-roadmap/>

IBM量子计算



Qubite	2	3	10	16	20	30	35	100	280
Classical bits required to represent an entangled state	512 bits	1,024 bits	16 kilobytes	1 megabytes	17 megabytes	17 gigabytes	550 gigabytes	more than all the atoms on the planet Earth	more than all the atoms in the universe

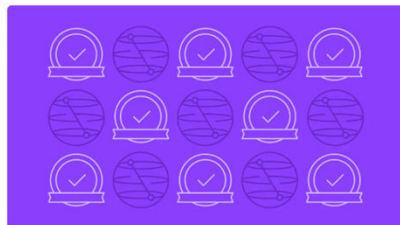


IBM量子计算

Latest news

Learn how quantum computers empower researchers to tackle problems that once seemed unsolvable.

[View all](#) →

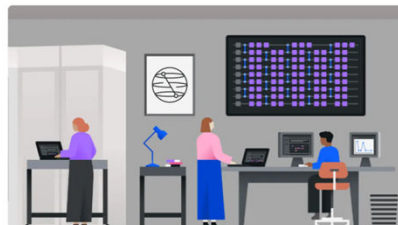


Boost your quantum credentials with new Qiskit v2.X developer certification

10 Sep 2025 • Gemma Dawson, Borja Peropadre, Luciano Bello, Robert Davis

[Enablement](#)

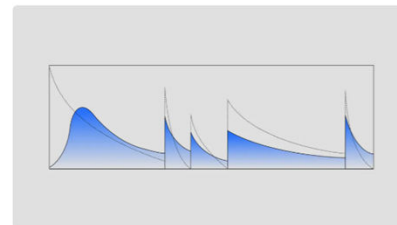
[Qiskit](#)



IBM Quantum Credits: Apply today for access to cutting-edge IBM quantum capabilities

13 Aug 2025 • Katie Harrison, Sieglinde Pfaendler, Sanskriti Deva, Leanne Cherry, Robert Davis

[Research](#)

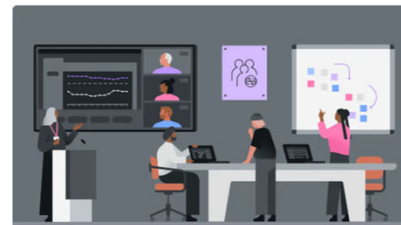


Relay-BP: The world's fastest, most accurate decoder for qLDPC error correction codes

4 Aug 2025 • Leanne Cherry

[Error Correction & Mitigation](#)

[Research](#)



Applications are open for the Qiskit advocate program

28 Jul 2025 • Radha Pyari Sandhir, Astri Cornish, Robert Davis

[Community](#)

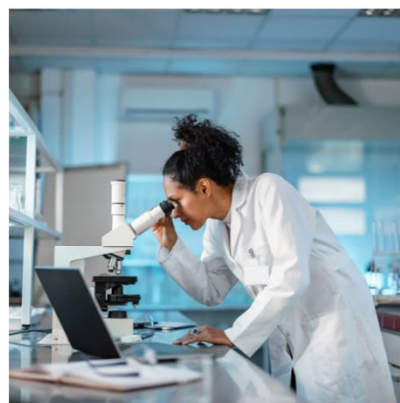
[Qiskit](#)



Moderna

[Read the story](#) ➤

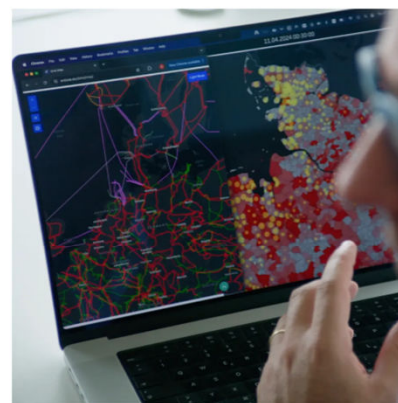
Envisioning a near-term quantum-enabled biotechnology pipeline.



RIKEN & Cleveland Clinic

[Read the story](#) ➤

Modeling chemistry for the future of drug discovery.

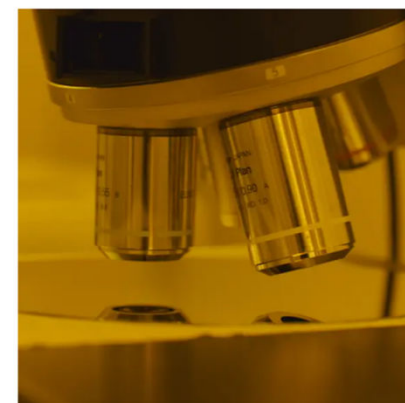


E.ON

[Watch the case study](#) 📺

Using quantum computing to help tackle electrical grid complexity.

[Read the story](#) ➤



JSR

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Charting a new future for the global semiconductor industry.

IBM量子计算

Development Roadmap

IBM Quantum

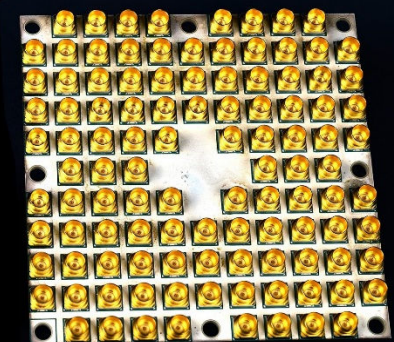
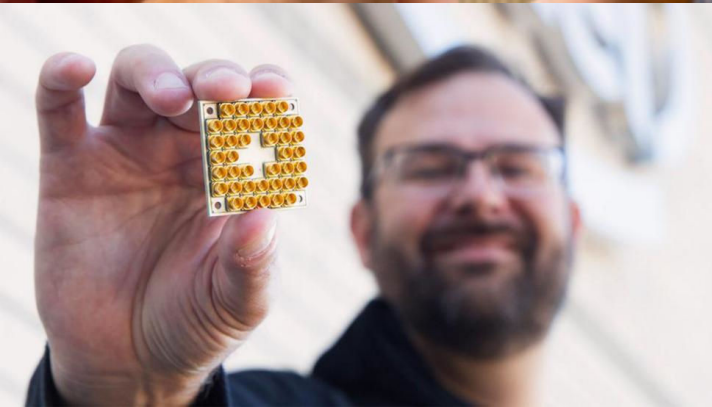
	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
	Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing
Data Scientist						Platform						
						Code assistant	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers						Middleware						
						Quantum Serverless	Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration		Circuit libraries
Quantum Physicist												
	IBM Quantum Experience		QASM3	Dynamic circuits	Execution Modes	Heron (5K)	Flamingo (5K)	Flamingo (7.5K)	Flamingo (10K)	Flamingo (15K)	Starling (100M)	Blue Jay (1B)
	Early	Falcon		Eagle		Error Mitigation	Error Mitigation	Error Mitigation	Error Mitigation	Error Mitigation	Error correction	Error correction
	Canary 5 qubits	Albatross 16 qubits	Penguin 20 qubits	Prototype 53 qubits		5k gates 133 qubits	5k gates 156 qubits	7.5k gates 156 qubits	10k gates 156 qubits	15k gates 156 qubits	100M gates 200 qubits	1B gates 2000 qubits
						Classical modular	Quantum modular	Quantum modular	Quantum modular	Quantum modular	Error corrected modularity	Error corrected modularity
						133x3 = 399 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits		

Innovation Roadmap

Software Innovation	IBM Quantum Experience ✓	Qiskit Circuit and operator API with compilation to multiple targets ✓	Application modules Modules for domain specific application and algorithm workflows ✓	Qiskit Runtime Performance and abstract through Primitives ✓	Serverless Demonstrate concepts of quantum centric-supercomputing ✓	AI enhanced quantum Prototype demonstrations of AI enhanced circuit transpilation ✓	Resource management System partitioning to enable parallel execution 🔄	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale ✓	Error correction decoder Demonstration of a quantum system with real-time error correction decoder ✓																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
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IBM Quantum / © 2023 IBM Corporation

Intel量子计算



Intel量子计算

A TIMELINE OF QUANTUM COMPUTING



PHENOMENOLOGICAL PHASE 1950s - 1990s

Primarily theoretical research, with limited physical experimentation



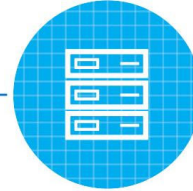
EXPERIMENTAL PHASE 1990s - 2000s

Establishment of fundamental mechanisms with physical apparatus



REALIZATION PHASE 2010s

Development of quantum processors and rudimentary quantum computers



SYSTEM PHASE 2015 - 2025

System-level engineering for practical quantum computers



COMMERCIAL PHASE 2025 and beyond

Production use of quantum computing systems to solve real-world problems



Fluid Dynamics



Astrophysics

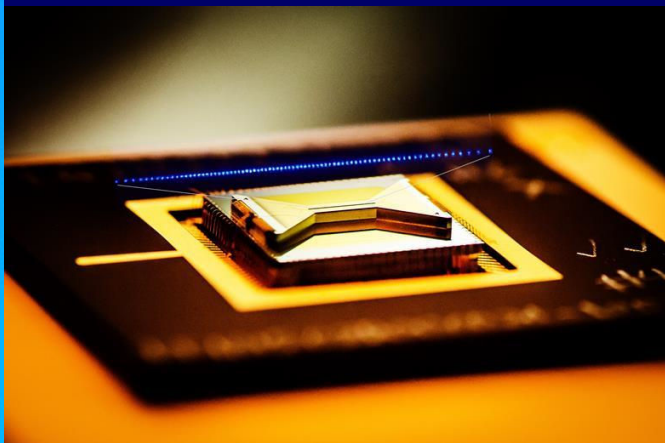


Materials Design

NEW IonQ breaks records for quantum computing performance ▶

A true quantum leap.

Introducing the first commercial trapped ion quantum computer. By manipulating individual atoms, it has the potential to one day solve problems beyond the capabilities of even the largest supercomputers.



The World's Most Advanced Quantum Computer

Our quantum cores use lasers pointed at individual atoms to perform longer, more sophisticated calculations with fewer errors than any quantum computer yet built. In 2019, leading companies will start investigating real-world problems in chemistry, medicine, finance, logistics, and more using our systems.

Preliminary benchmark test results on IonQ hardware as of December 10, 2018.

Qubits

Qubits are the basic unit of information storage on a quantum computer. After they're initialized, logical operations—called gates—are performed on them.

Maximum loaded 160 qubits

Single-qubit gates performed on up to 79 qubits

Two-qubit gates performed on all pairs of up to 11 qubits

Error Rate

Gate fidelity is a measure of the accuracy of a single gate. Gates that manipulate one qubit at a time are less complex and less error-prone than gates that operate on two qubits. The following benchmarks were captured on a fully-connected 11-qubit configuration.

Average fidelities

Single-qubit gates >99%

Two-qubit gates >98%*

Best fidelities

Single-qubit gates 99.97%

Two-qubit gates 99.3%*

Minimum fidelities

Single-qubit gates >99%

Two-qubit gates >96%*

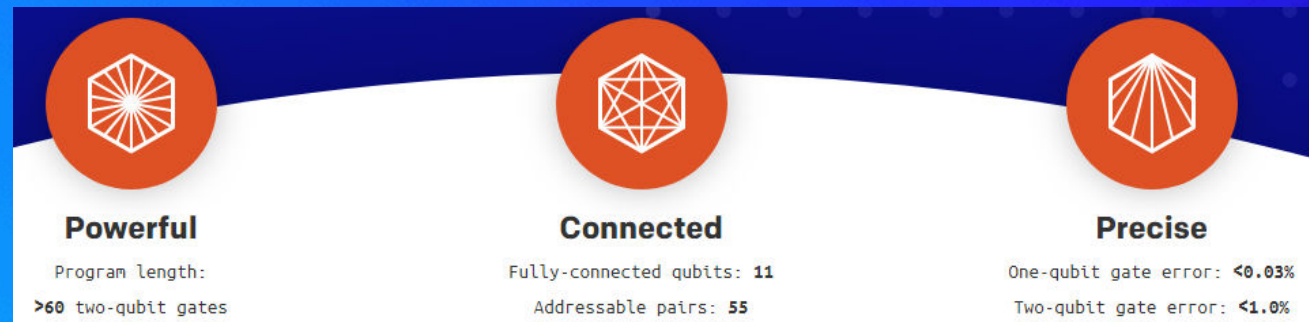
* not corrected for state preparation and measurement errors.

Benchmark: Bernstein-Vazirani Algorithm

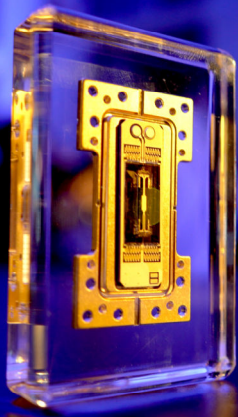
The Bernstein-Vazirani Algorithm is a basic test of the ability of a quantum computer to simultaneously evaluate possibilities that conventional computers must calculate one at a time. The complexity of the test is determined by the maximum length in bits of an oracle—an arbitrary number the computer must determine.

10-qubit oracle success rate 73.0%

Classical computer success rate ~0.2%



IonQ



	IonQ Aria	Forte	Forte Enterprise
	Learn More	Learn More	Learn More
System Availability			
Commercial Availability	✓	✓	✓
System Sales	—	✓	✓
Performance			
Algorithmic Qubits (#AQ)	#AQ 25	#AQ 36	#AQ 36 Target
Physical Qubits	25	36	36
2QG Fidelity	99.4%	99.6%	99.6% Target
1QG Fidelity	99.94%	99.98%	99.98% Target
Specifications			
Connectivity	All-to-all	All-to-all	All-to-all
Operating System	First Gen	First Gen	First Gen
Laser System	Acousto-Optic Modulator	Acousto-Optic Deflector	Acousto-Optic Deflector
Error Mitigation	✓	✓	✓

IonQ Roadmap for Large-Scale, Fault-Tolerant Quantum Computers

Built on pioneering trapped ion research, IonQ's roadmap is enabled by the nearly 1,000 patented hardware and software breakthroughs that were developed at IonQ integrated from strategic acquisitions.



Original IonQ #AQ Roadmap

2024	2025	2026	2027	2028
36 Algorithmic Qubits	64 Algorithmic Qubits	256 Algorithmic Qubits	384 Algorithmic Qubits	1,024 Algorithmic Qubits

Updated Technology Roadmap

2024	2025	2026	2027	2028	2029	2030
Commercial Quantum Computers 36 Physical Qubits 99.96% Physical Qubit Fidelity All-to-All Connectivity Optical Gate Operations 1D Qubit Array	Commercial Quantum Computers 64 Physical Qubits 99.99% Physical Qubit Fidelity All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Parallel Operations	Commercial Quantum Computers 256 Physical Qubits 99.99% Physical Qubit Fidelity 12 Logical Qubits <1.00E-7 Logical Error Rate All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Parallel Operations	Commercial Quantum Computers 10,000 Physical Qubits 99.99% Physical Qubit Fidelity 800 Logical Qubits <1.00E-7 Logical Error Rate All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Parallel Operations	Commercial Quantum Computers 20,000 Physical Qubits 99.99% Physical Qubit Fidelity 1,600 Logical Qubits <1.00E-7 Logical Error Rate All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Photonic Interconnect Parallel Operations	Commercial Quantum Computers 200,000 Physical Qubits 99.99% Physical Qubit Fidelity 8,000 Logical Qubits <1.00E-12 Logical Error Rate All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Photonic Interconnect Parallel Operations	Commercial Quantum Computers 2,000,000 Physical Qubits 99.99% Physical Qubit Fidelity 80,000 Logical Qubits <1.00E-12 Logical Error Rate All-to-All Connectivity Microwave Gate Operations 2D Qubit Array Mid-Circuit Measurement Photonic Interconnect Parallel Operations
Development Systems 36+ Physical Qubits	Development Systems 64-100+ Physical Qubits	Development Systems 100-256+ Physical Qubits				

Examples of Expected Commercialization Opportunities Unlocked

AI/ML	Synthetic Data Generation	More Parameters
Optimization	Structural Analysis In CAE	More Mesh Points Modeled
Simulation	Chemical Reaction Modeling	More Orbitals
AI/ML	LLM Fine-Tuning	Higher Accuracy
Optimization	Unit Commitment In Electric Grids	More Variables
Simulation	Protein Folding For Drug Discovery	Larger Peptides
AI/ML	Image Change Detection	Higher Accuracy
Optimization	Vehicle Routing	More Variables
Simulation	Laminar Fluid Dynamics	More Complex Models
AI/ML	AI Agent Assignment	More Agents
Optimization	Fantasy Sports Team Picking	More Dimensions Modeled
Simulation	Drug-Target Affinity Prediction With Solvent Model	Larger Molecules
AI/ML	Medical Imaging Analysis	Higher Resolution
Simulation	Battery Materials Discovery	More Complex Models
Simulation	Pharma Catalysts Redesign	More Orbitals
Optimization	Institutional Portfolio Rebalancing	More Assets
AI/ML	Training Robotic AI Models	More Parameters
AI/ML	Quantum Federated Learning	More Parameters
Optimization	Optimization Of AI Agent Action Planning	More Actions
Simulation	Materials Discovery For Advanced Medical Equipment	More Complex Models
Simulation	Carbon Capture Catalyst Design	Larger Molecules
Simulation	Polymorph Screening For Drug Discovery	Larger Molecules

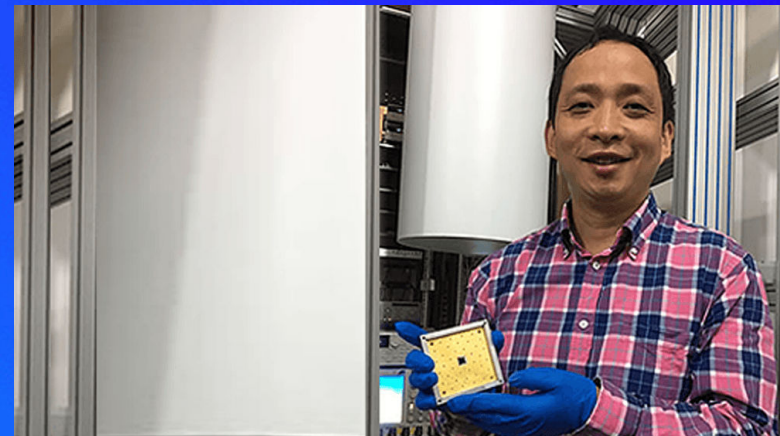
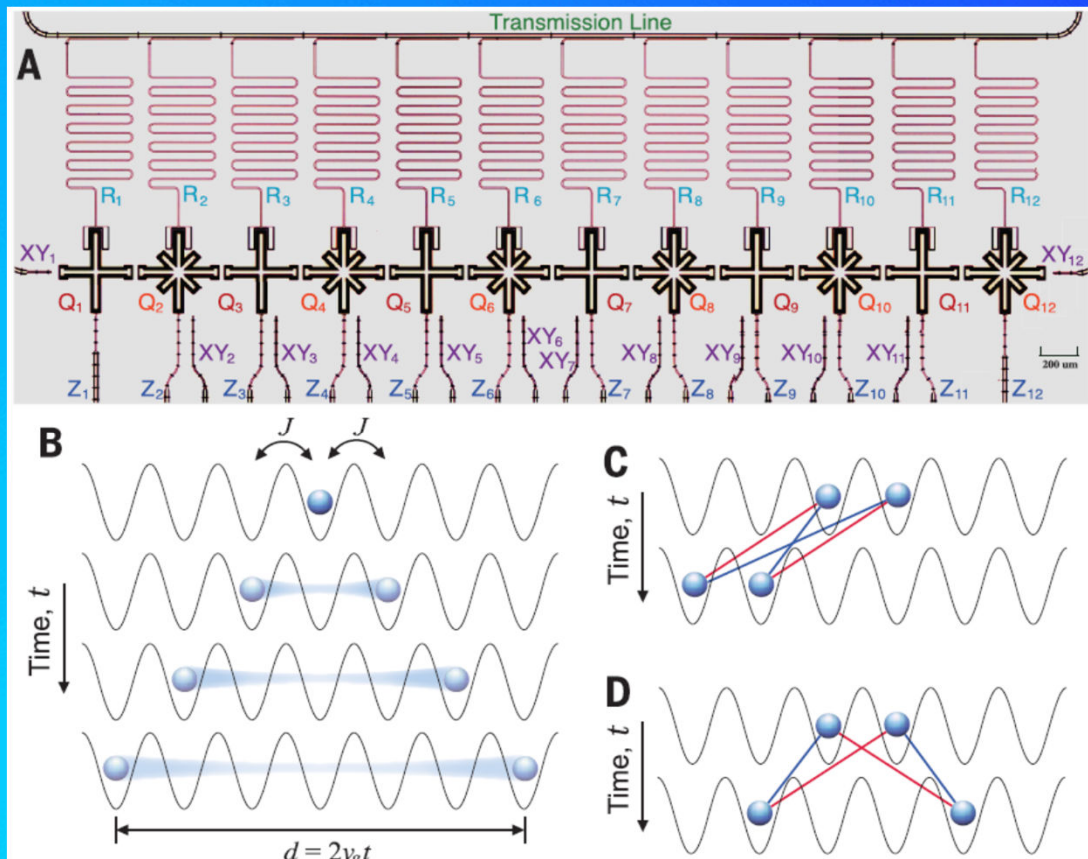
Broad Quantum Advantage



我国量子计算

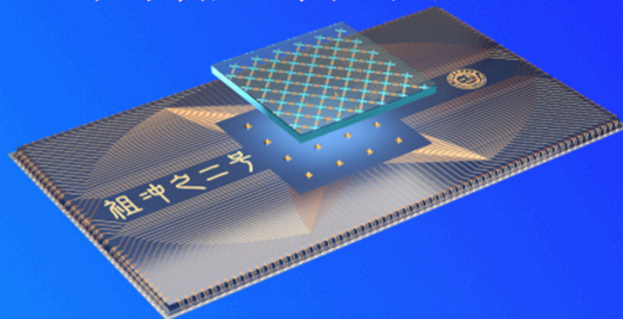
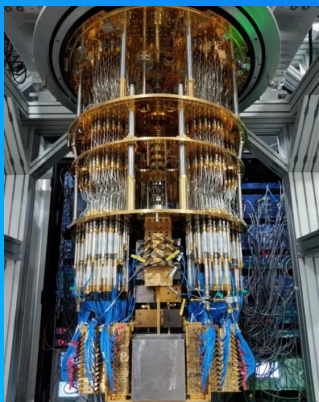
USTC, 清华, 浙大, 中科院等; 阿里巴巴, 腾讯, 百度, 华为等

Yan *et al.*, Science 364, 753–756 (2019)



我国量子计算

USTC, 清华, 浙大, 中科院等; 阿里巴巴, 腾讯, 百度, 华为等



66比特可编程超导量子计算原型机“祖冲之二号”



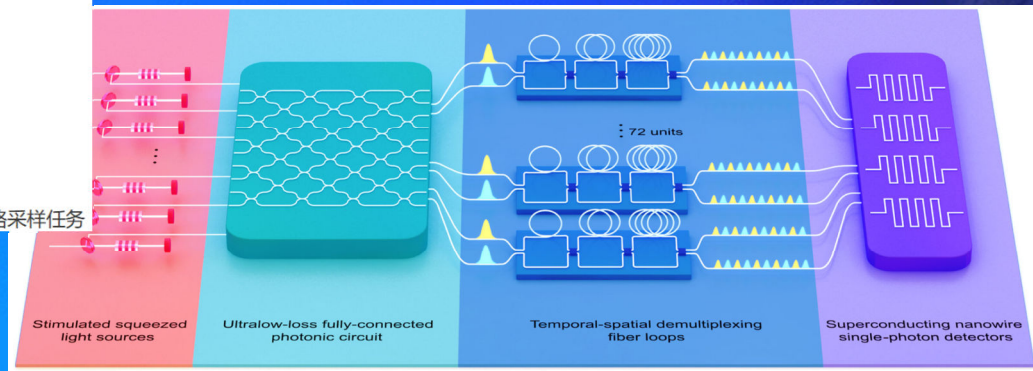
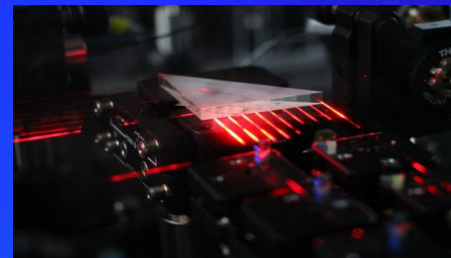
可编程二维 62 比特超导处理器“祖冲之号”的量子行走



图:祖冲之三号芯片示意图。105个可读取比特和182个耦合比特集成在同一个芯片上执行量子随机线路采样任务

“祖冲之三号”

113个光子
144模式的
量子计算原型机
“九章二号”



255个光子的量子计算原型机“九章三号”

D-Wave

It's Time to Start Your Quantum Journey

Don't be left behind. Forward-thinking organizations see quantum as an opportunity to leap ahead of the competition. From finding efficiencies and reducing waste to decreasing time to solution and solving problems abandoned due to complexity, the business value is real.

[Get Access to the Quantum Computing Industry Report](#)

40% of large enterprises surveyed are already experimenting with quantum computing.

Source: 451 Research

D:wave

QBTS
LISTED
NYSE

advantage2

NEXT-GENERATION
EXPERIMENTAL PROTOTYPE

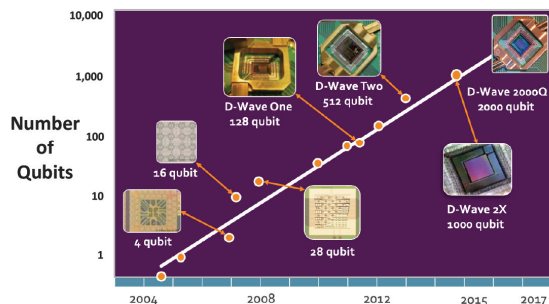
Get Business Advantage

From 25 hours of work to 2 minutes per week. 80% less manufacturing waste. 60% return on investment. 57% reduction in emissions. This is what quantum can do today for real-world applications.

[Explore Customer Success Stories](#)

D-Wave

D-Wave Product Generations



4,400+ Qubits
Solve more complex computational problems

40,000+ Couplers
Dense connectivity supports compact, high-fidelity problem embeddings

20-Way Connectivity*
Zephyr™ topology enables embedding of more complex problems

40% Higher Energy Scale*
Contributes to faster time-to-solution and high-quality results

2x Coherence*
Enhances overall performance and drives faster time-to-solution

4x Lower Noise*
Reduces noise for enhanced solution stability

Fast Anneal
Enables quicker, more coherent quantum computations

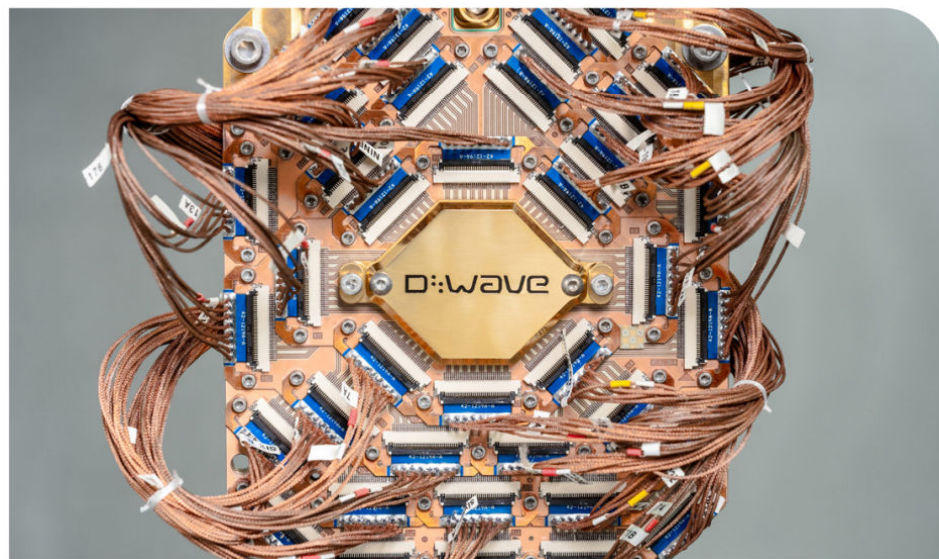
Hybrid Solver Integration
Enables scaling via quantum-hybrid computing, with support for up to 2 million variables

*Compared to the D-Wave Advantage system

D-WAVE

advantage2™
QUANTUM COMPUTER

Production-Ready
Quantum Performance
for Business and Science

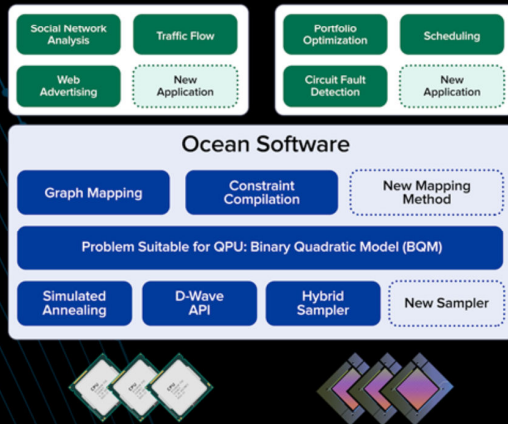


D-Wave



Accelerate Quantum Development with Ocean

The Ocean software fits between applications and the compute resources.



5000+
Qubits

A world-class annealing quantum processor design with continued growth in qubits, connectivity, and coherence.

1 Million
Variables

Built to support real-world size applications with up to 1 million variables and 100,000 constraints via our quantum-classical hybrid solver service in Leap.

250+
Applications

More than 250 early applications across domains like manufacturing, financial services, and life sciences already exist using D-Wave quantum systems today.

D-Wave

Customer Spotlight

D-Wave's annealing quantum computers are supporting enterprise production applications and pioneering research and scientific breakthroughs.



Optimization

Ford Otosan created a hybrid quantum application utilizing D-Wave quantum technology to optimize vehicle production sequencing in the body shop, reducing scheduling of 1,000 vehicles from 30 minutes to less than 5 minutes, a 6x improvement.

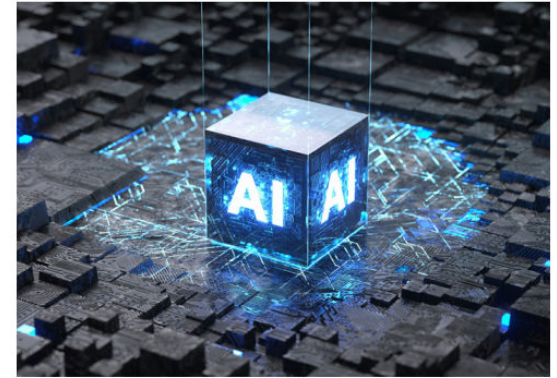
Learn more [here](#).



Research

The Jülich Supercomputing Centre uses a D-Wave Advantage system to facilitate breakthroughs in quantum AI and quantum optimization and expects to connect it with the JUPITER supercomputer, Europe's only exascale HPC for advanced research.

Learn more [here](#).



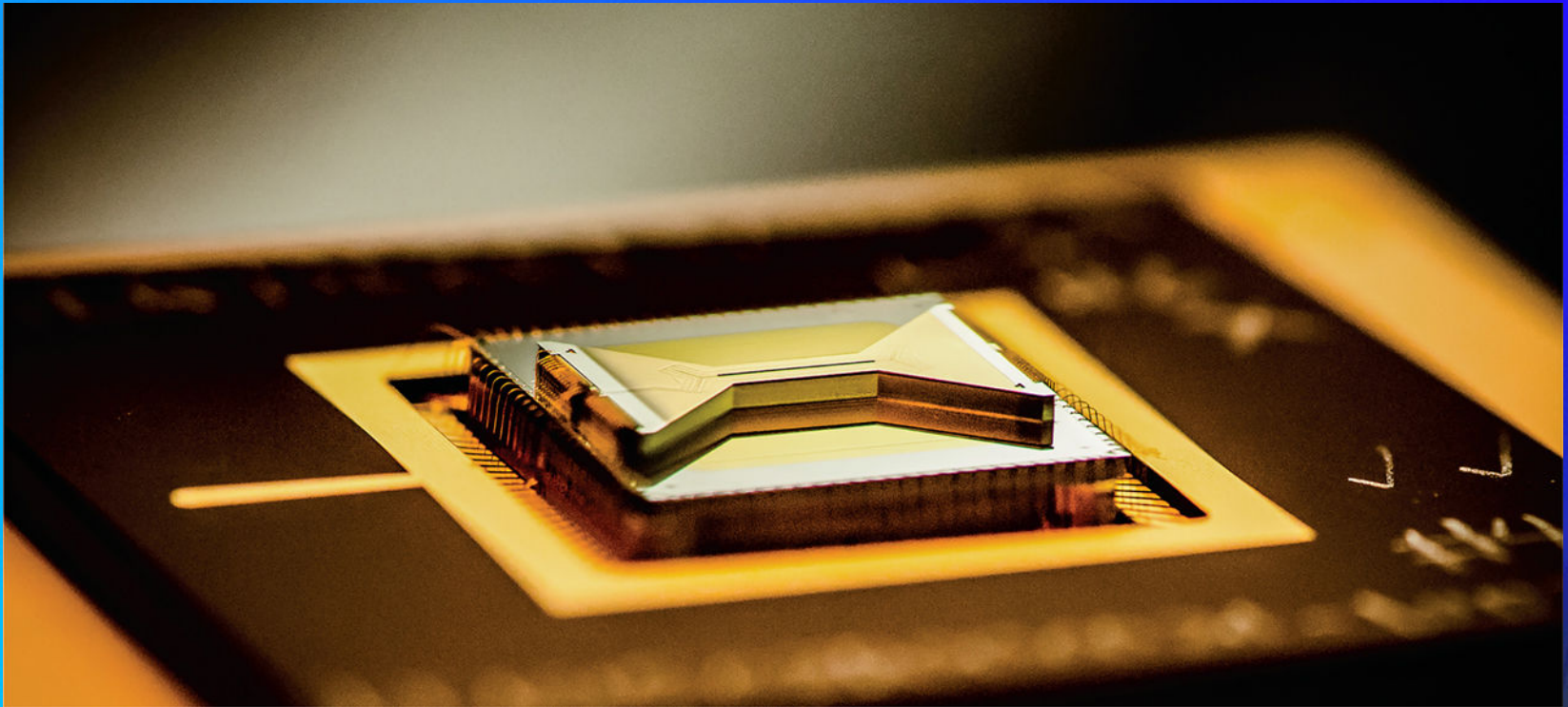
AI

Japan Tobacco leveraged D-Wave's quantum hybrid workflow to improve Large Language Model training for early-phase drug discovery. The quantum-enhanced approach achieved better learning accuracy with fewer parameters than classical methods.

Learn more [here](#).

美国能源部推进量子计算

A chip that traps ions is the basis for a Department of Energy testbed quantum computer.



Adrian Cho Science 2018;359:141-142



美国能源部推进量子计算

A quantum computing to-do list

Researchers have several general ideas for scientific applications of quantum computers.

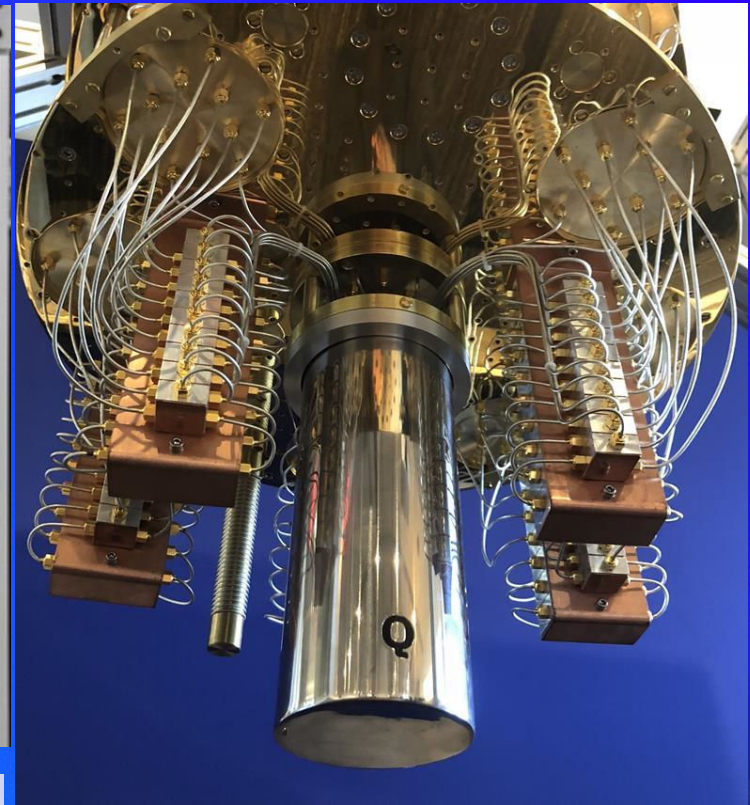
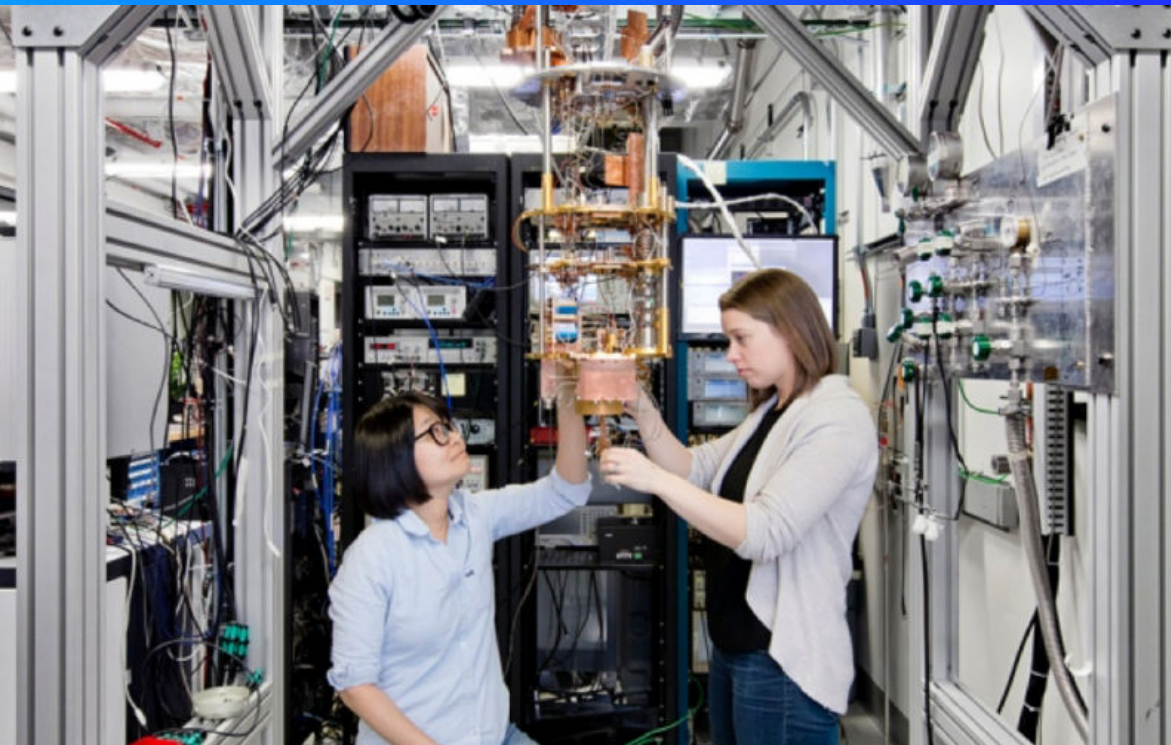
FIELD	TASK
Chemistry	Calculate molecules' energies and structures, model catalysis.
Materials science	Design novel materials from the atom up.
Nuclear physics	Calculate energies and structures of nuclei and particles such as protons.
Particle physics	Optimize search for subtle signals.

Adrian Cho Science 2018;359:141-142

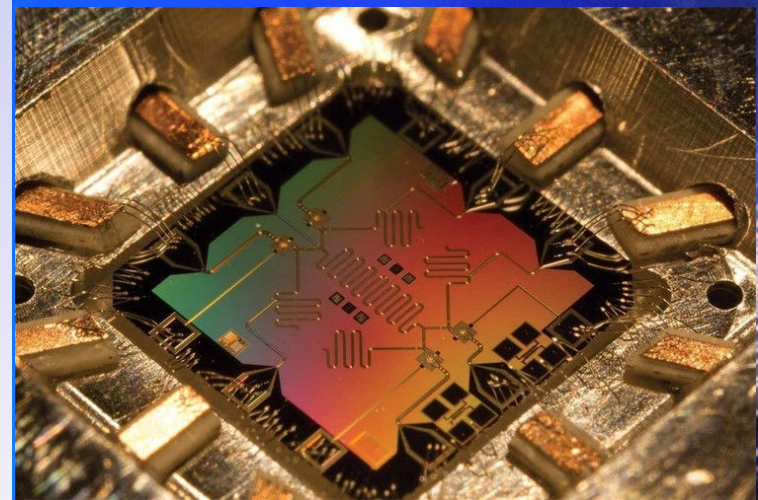
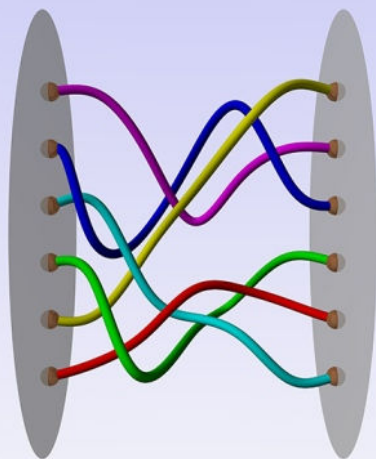
DOE Office of Science: Contributions to Quantum Computing

Support for quantum computing research originated in the Advanced Scientific Computing Research program in 2017 and rapidly spread across the Office of Science. The research portfolio now includes applications in nuclear and particle physics, plasma science, chemistry, and materials. It also includes improving the fundamental building blocks of quantum computers, developing sophisticated control to make the most of any group of qubits, and computer science research that will ultimately make quantum computers easier to use.

量子计算机竞赛

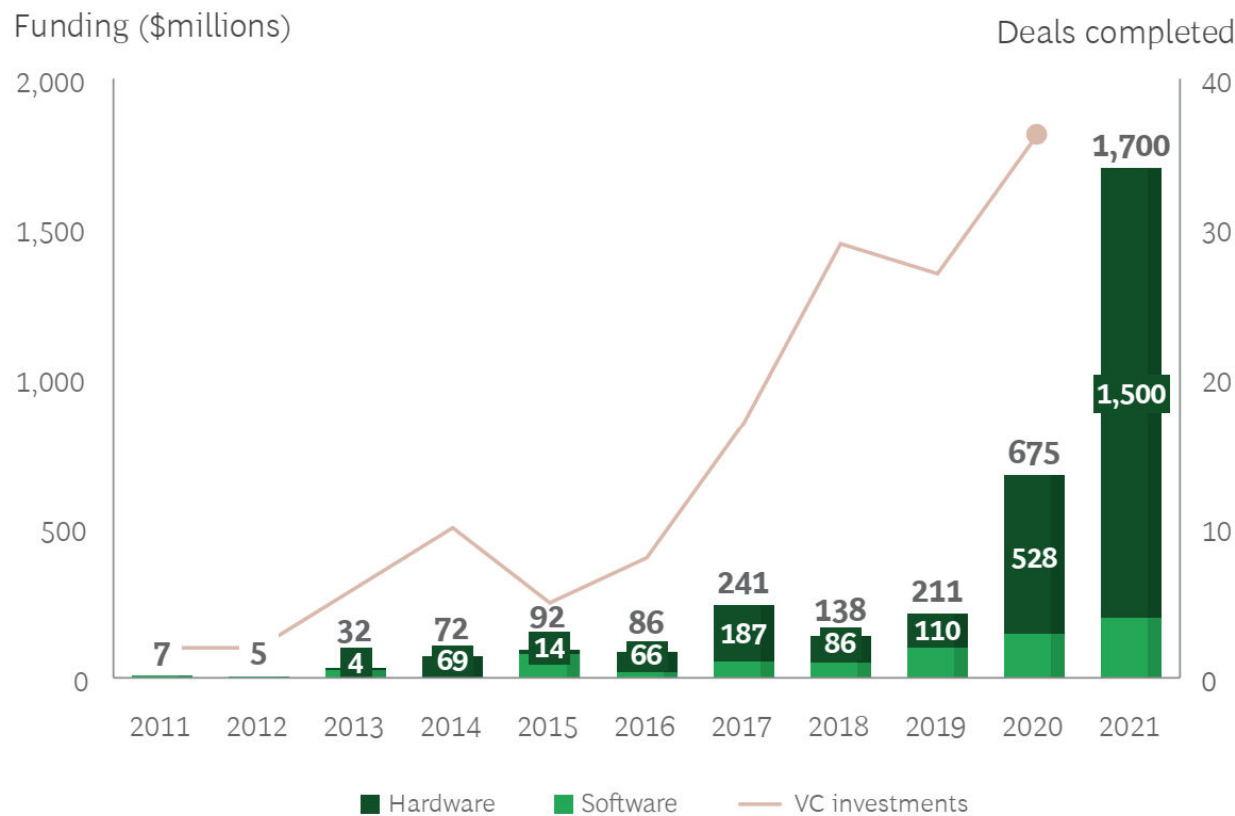


Google,
IBM, 微软,
Intel 等



量子计算

Exhibit 1 - Acceleration of Investments in Quantum Computing



Top 3 investments in 2021



PsiQuantum

\$450 million raised
(Series D)



Xanadu

\$100 million raised
(Series B)



IONQ

\$650 million raised
($\frac{1}{3}$ PIPE + SPAC)

Sources: PitchBook; BCG analysis.

Note: PIPE = private investment in public equity; SPAC = special-purpose acquisition company.

2022年8月25日，波士顿咨询集团（BCG）发布的研究报告

《Can Europe Catch Up with the US (and China) in Quantum Computing?》

中国科学技术大学 陈凯

量子计算

Exhibit 2 - Quantum Computing Will Create Value Across Several Industries and Use Cases

	Applications	Private landscape Value creation potential (\$billions) ¹	
		Low	High
Cryptography (\$40 billion to \$80 billion)	Encryption/decryption	40	80
	Aerospace: Flight route optimization	20	50
Optimization (\$100 billion to \$220 billion)	Finance: Portfolio optimization	20	50
	Finance: Risk management	10	20
	Logistics: Vehicle routing/network optimization	50	100
	Automotive: Automated vehicles, AI algorithms	0	10
Machine learning (\$150 billion to \$220 billion)	Finance: Fraud and money laundering prevention	20	30
	High tech: Search and ads optimization	50	100
	Other: Varied AI applications	80+	80+
Simulation (\$160 billion to \$330 billion)	Aerospace: Computational fluid dynamics	10	20
	Aerospace: Materials development	10	20
	Automotive: Computational fluid dynamics	0	10
	Automotive: Materials and structural design	10	15
	Chemistry: Catalyst and enzyme design	20	50
	Energy: Solar conversion	10	30
	Finance: Market simulation (e.g., derivatives pricing)	20	35
	High tech: Battery design	20	40
	Manufacturing: Materials design	20	30
	Pharma: Drug discovery and development	40	80

Sources: Academic research; industry interviews; BCG analysis.

¹Represents value creation opportunity of mature technology.

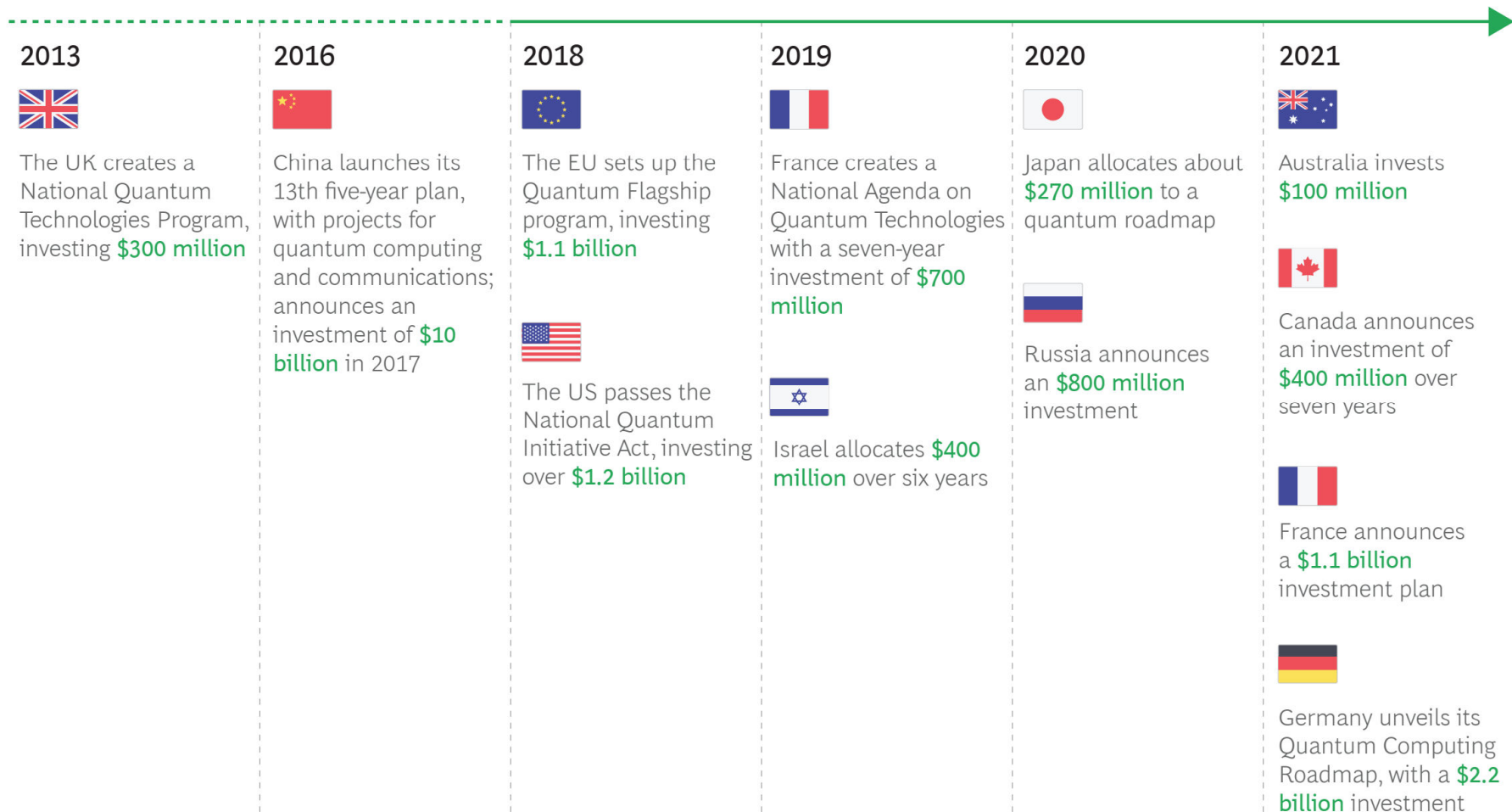
2022年8月25日，波士顿咨询集团（BCG）发布的研究报告

《Can Europe Catch Up with the US (and China) in Quantum Computing?》

中国科学技术大学 陈凯

量子计算

Exhibit 3 - The EU's Competitive Start in Quantum Computing



Sources: Literature search; BCG analysis.

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Exhibit 4 - The 2022 Quantum Computing Country Rankings

Tiers			 Government support	 Private initiative	 Talent
1	US		Tier 1 Front-runners and top performers, positioned to lead globally	   	   
2	China EU UK	  	 	    	
3	Australia Canada	    	     	        	
4	Israel Japan Russia Switzerland	   	 	       	

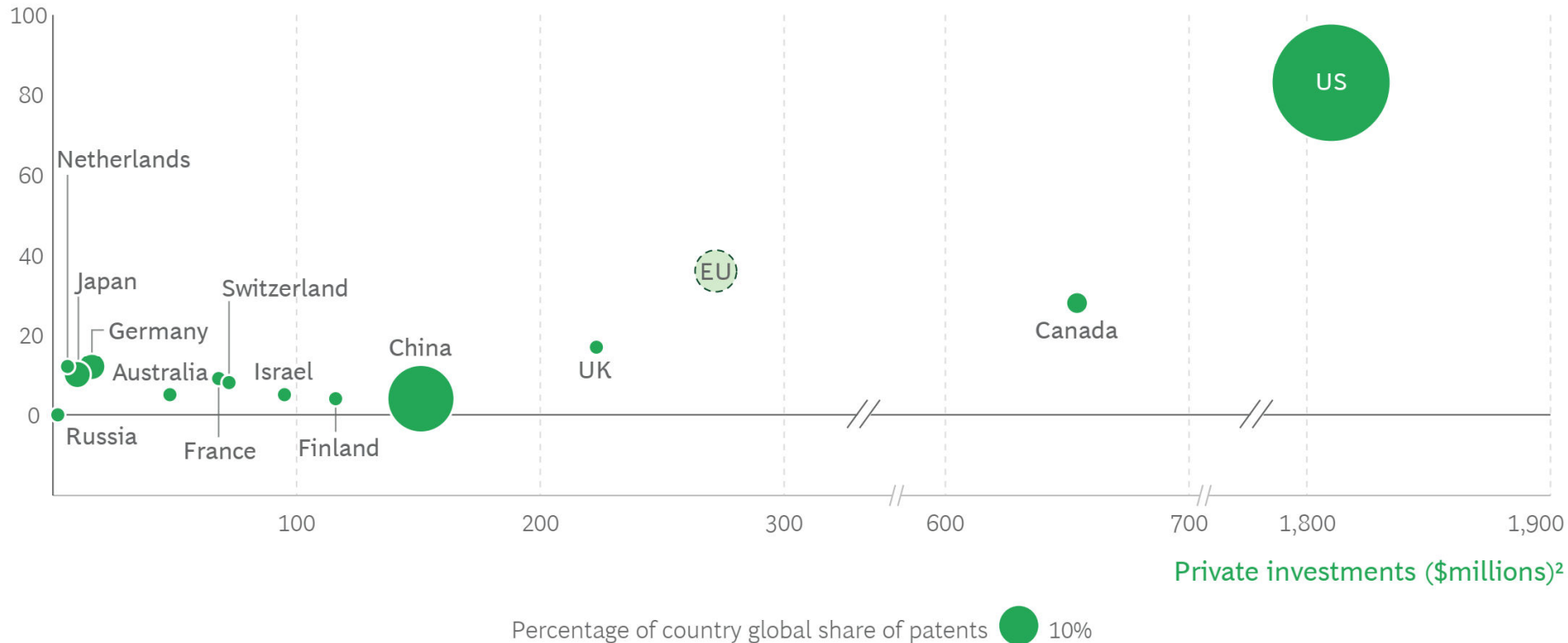
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Exhibit 7 - The US Has the Most Startups, Private Investments, and Patents in Quantum Computing

Estimated number of companies¹

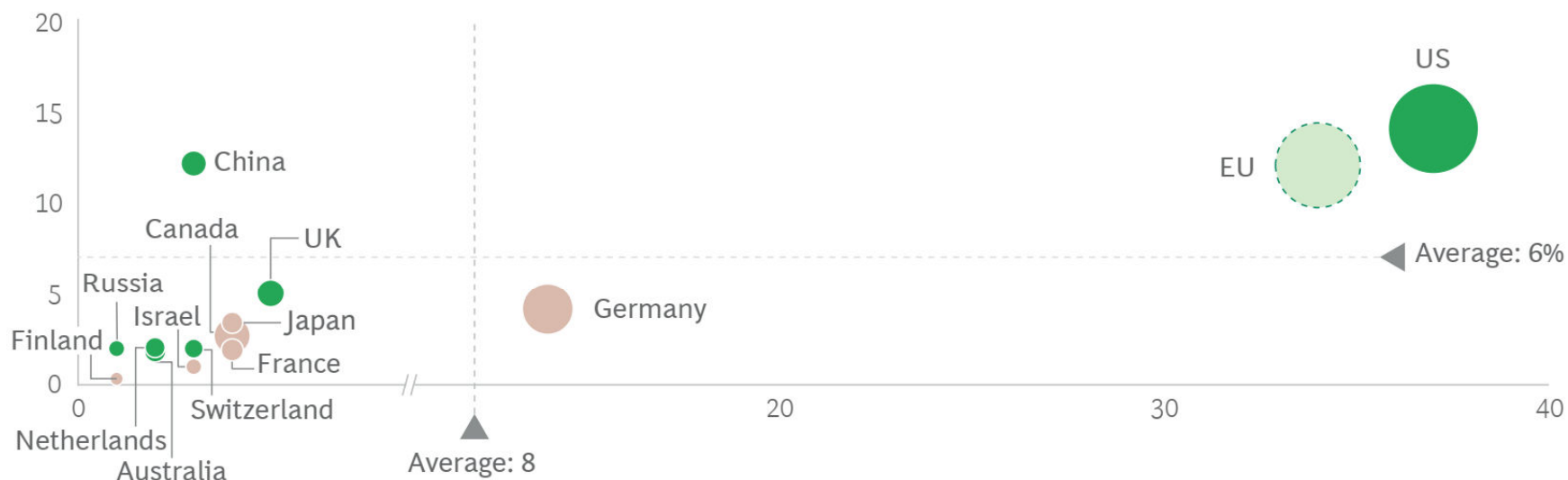


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Exhibit 8 - The EU Is Second Only to the US in Scientific and Educational Capabilities

Scientific articles on quantum computing, by country, in 2021 (%)



Number of universities ranked in the Top 100 for quantum computing

● Countries with policies that target quantum education

● Number of students in universities 250,000

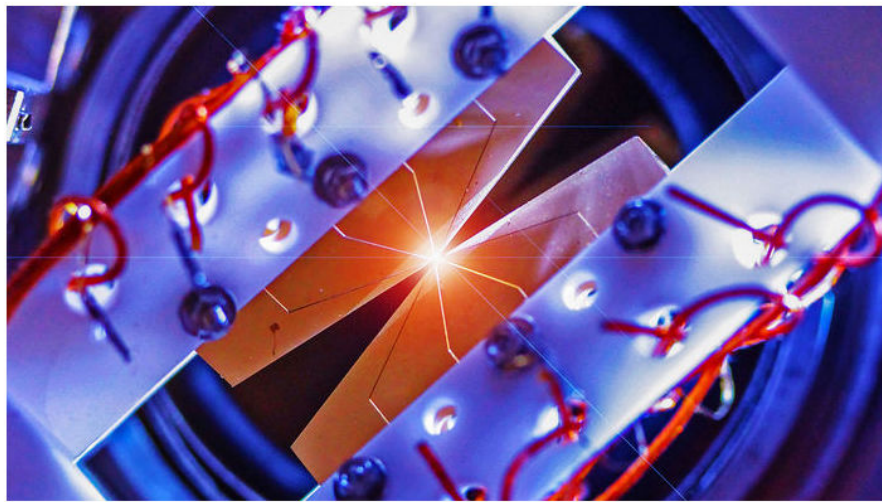
Sources: EduRank; Web of Science; Literature search; BCG analysis.

Note: The number of articles and universities for the EU represents the sum of the individual totals for each EU country.

2022年8月25日，波士顿咨询集团（BCG）发布的研究报告

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美国推进国家量子计划



Ions trapped between gold blades serve as information-carrying qubits in a prototype quantum computer. E. EDWARDS/JOINT QUANTUM INSTITUTE

Update: Quantum physics gets attention—and brighter funding prospects—in Congress

By Gabriel Popkin | Jun. 27, 2018, 12:30 PM



COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

National Quantum Initiative Act

The National Quantum Initiative Act establishes a federal program to accelerate quantum research and development for the United States' economic and national security.

美国推进量子网络战略构想



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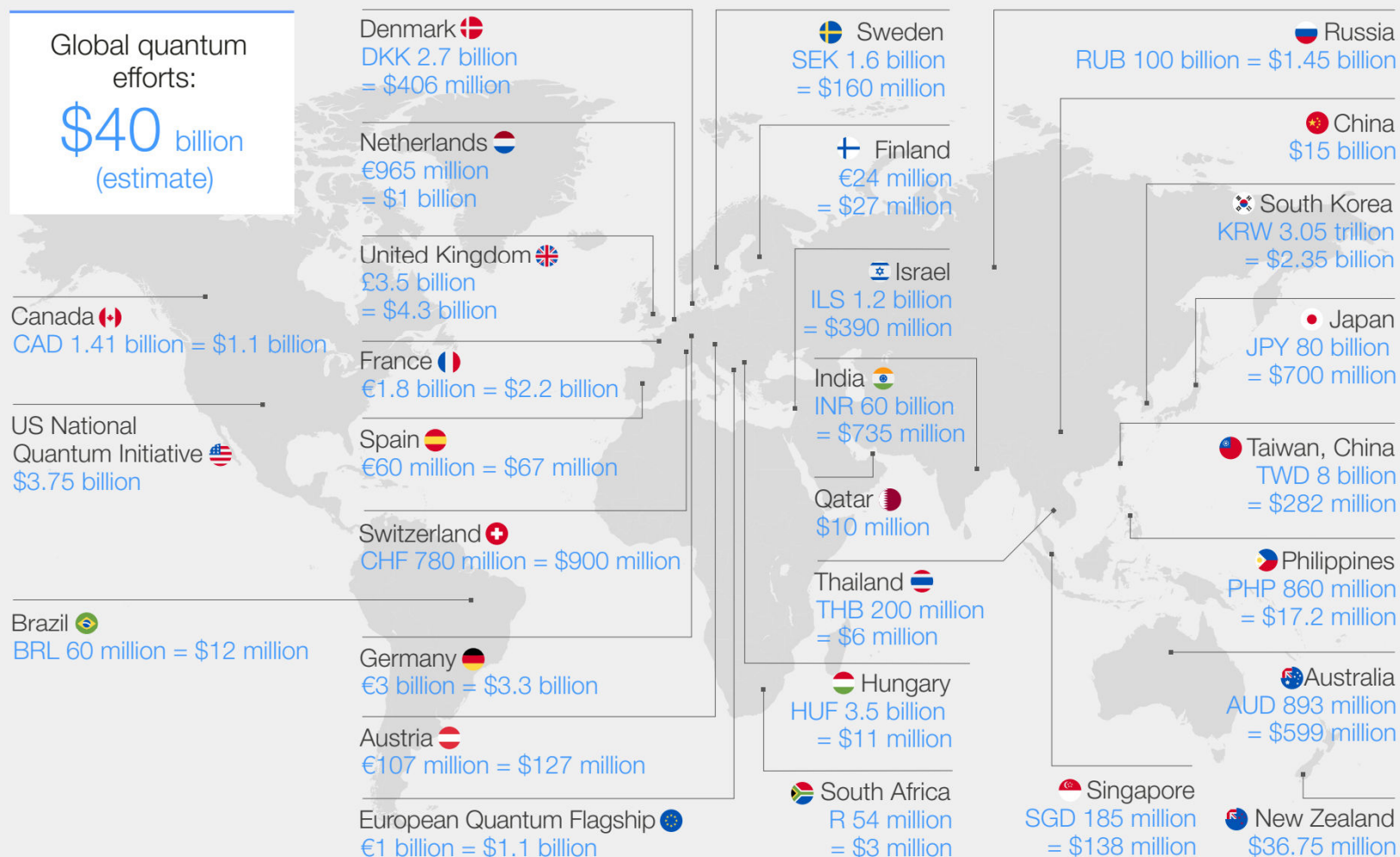
February 2020



世界范围内的量子技术

FIGURE 1

Public sector investments in quantum technologies worldwide



Note: Not exhaustive; timelines for funding vary by country.

Sources: "Overview of Quantum Initiatives Worldwide 2023", QURECA, 19 July 2023, <https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/>;
Department of Industry, Science and Resources, Australia; ETH Domain (ETH Zurich, EPFL, PSI).

量子信息能做什么？



寄语同学们

习近平主席：科大是一所很值得敬重的大学，同学们应该为能在科大学习感到自豪。同学们要做有理想、有追求的大学生，做有担当、有作为的大学生，做有品质、有修养的大学生。

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希望大家做胸怀家国、志存高远的“追梦人”，以爱国情怀引领人生航向。
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希望大家做向阳而生、乐观积极的“生活家”，以充盈灵魂滋养青春气象。



课程安排

- ◆ **绪论** 量子信息概念，历史和展望
- ◆ **第一章 量子体系** 量子态，Schmidt分解，混合态，密度矩阵，量子测量，量子不可克隆定理等。
- ◆ **第二章 量子纠缠** 纠缠和可分型，纠缠判据，纠缠量化，多粒子推广等
- ◆ **第三章 量子关联表现** 局域实在论，Bell不等式，多体推广，纠缠与非定域性的关系等
- ◆ **第四章 量子通信** 量子通信方案，通信基本形式包括量子隐形传态、稠密编码，量子密钥分发等；非理想条件下量子保密通信方案和实验，数据处理方法，安全性分析；与纠缠关系
- ◆ **第五章 量子纠错** 量子纠错码，原理、构造、应用
- ◆ **第六章 量子计算** 量子算法、应用
- ◆ **新进展：**量子成像等（徐飞虎老师）

谢谢

<http://quantum.ustc.edu.cn/>
<http://www.quantumcas.ac.cn/>

练习题

1. 实验上随机地以 $|C_0|^2$ 的几率制备 $|0\rangle$ ，并以 $|C_1|^2$ 的几率制备 $|1\rangle$ 。这样类型的量子态如何刻画与描述？比较其与量子态 $C_0|0\rangle + C_1e^{i\theta}|1\rangle$ 的异同（ C_0, C_1 , 和 θ 均为实数）。
2. 以光学实验的偏振量子态为例，用半波片和四分之一波片的组合从 $|0\rangle$ 态制备 $C_0|0\rangle + C_1e^{i\theta}|1\rangle$ 。对于实现任意的单量子比特么正变换，试探索分析这样的组合最少的波片数目为多少，如何操作？