Tecnologie quantistiche: la nuova frontiera di Scienza e Innovazione

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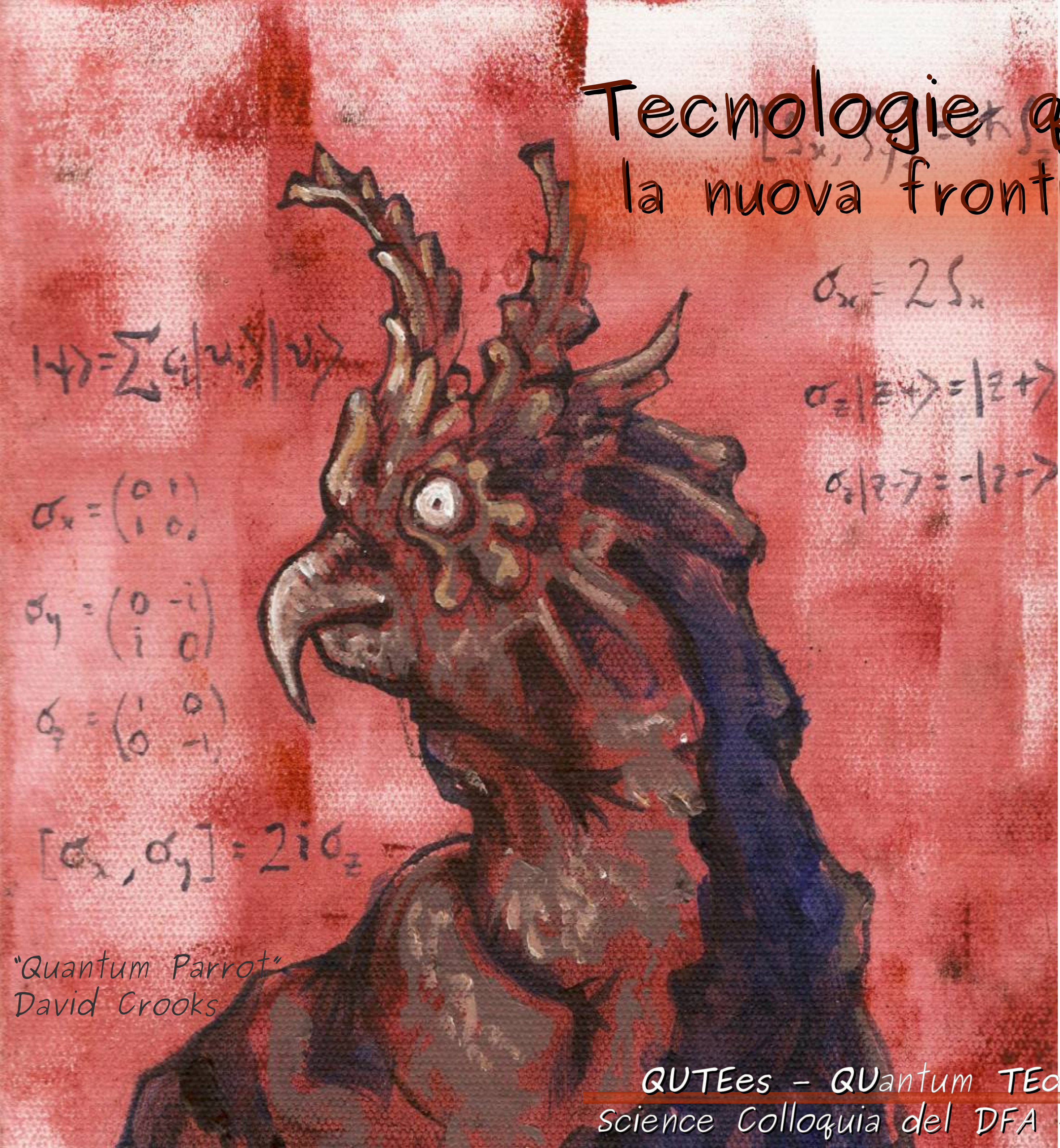


"Quantum Parrot"
David Crooks

QUTEes - QUantum TEchnologies Theory group

Science Colloquia del DFA - Catania 7 Giugno 2017

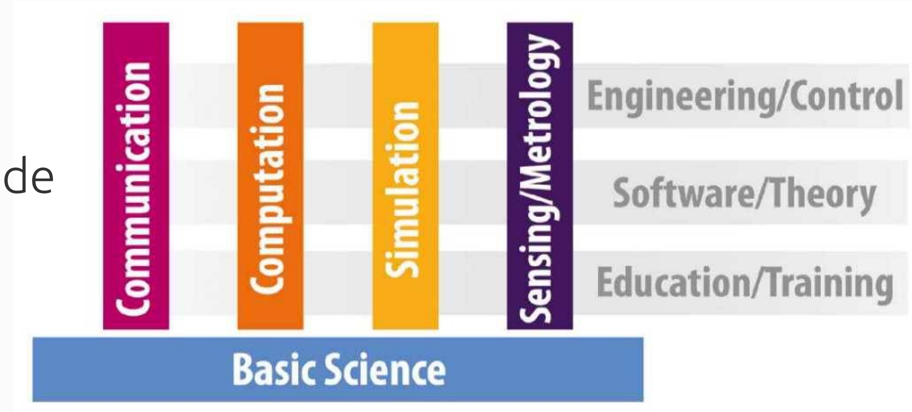
the ambition of quantum technologies

- "Quantum Technologies" an interdisciplinary umbrella, encompassing physics, chemistry, mathematics, computer science, engineering
- With possibly important social and scientific impact on all disciplines

understanding the **NEW** physics governing
large complex & genuinely quantum
(open) networks
quantum control → **quantum supremacy**

- **mysteries** of Quantum Mechanics **put at work**
  - Computation, Simulation, Communication, Sensing, Basic Science
- defy the standard paradigm: macroscopic systems **decohere** and behave classically and build **new physical systems** where **new physical contexts** appear.

- New Research and Innovation programs worldwide
  - **EU Flagship on "Quantum Technologies"**



Activity in Catania
Condensed Matter & Quantum Technologies

- GF
- Giuseppe Angilella
- Luigi Amico
- Elisabetta Paladino
- many other Collaborators and Students over the years

letters to nature

NATURE | VOL 407 | 21 SEPTEMBER 2000 | www.nature.com

Detection of geometric phases in superconducting nanocircuits

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letters to nature

NATURE | VOL 416 | 11 APRIL 2002 | www.nature.com

Scaling of entanglement close to a quantum phase transition

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REVIEWS OF MODERN PHYSICS, VOLUME 86, APRIL–JUNE 2014

$1/f$ noise: Implications for solid-state quantum information

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Entanglement in many-body systems

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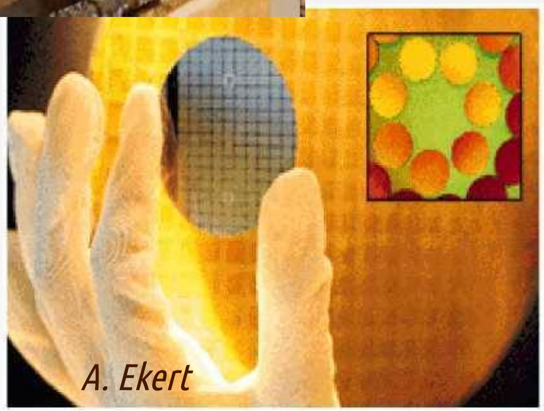
(Published 6 May 2008)

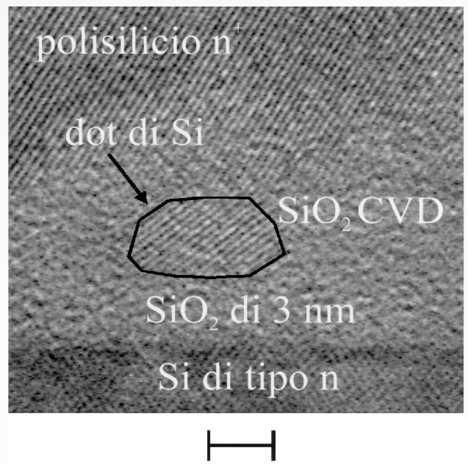
nanoelectronics: quantization → coherence

New theoretical areas emerge from forefront technological problems and viceversa
The development of information technology brings us back to **quantum mechanics**
(of open quantum systems)

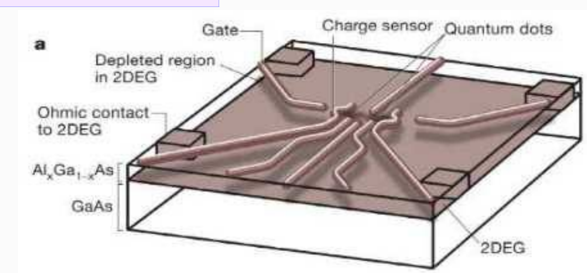
Quantum solids
Semiclassical
transport



Present day nano-electronics
Quantization
Incoherent Quantum Nano-systems

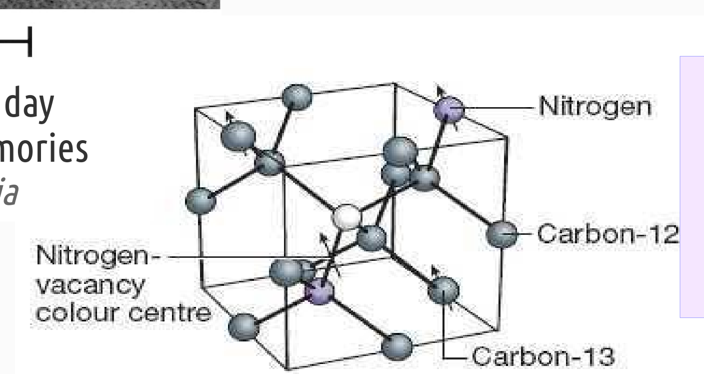


… as in a present day floating gate memories
@CNR-IMM Catania



Mesoscopic systems
Coherent Transport

"[…] it seems that the laws of physics present no barrier to reducing the size of computers until bits are of the size of atoms and quantum behaviour holds."
(R. Feynman, 1985)

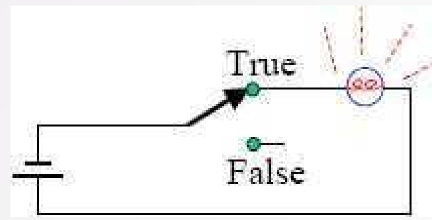


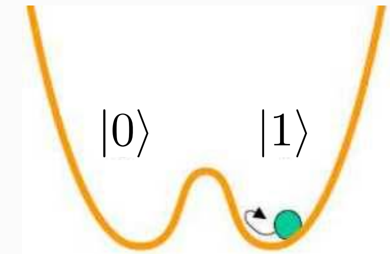
Design and **quantum control** of atomic size architectures

Williams Clearwater §1

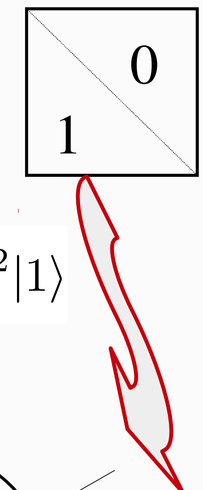
superposition postulate at work
classical bits vs qubits

- **Encoding a classical bit**: $\{0,1\}$
  answer to a "yes-no" question
  = 1 bit of information



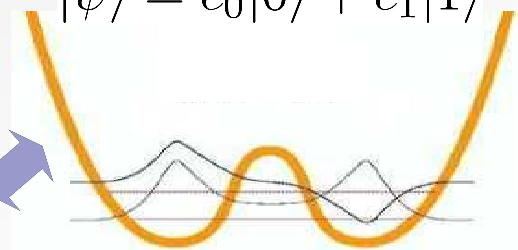


May be implemented by two "classical states" of a physical (quantum) system



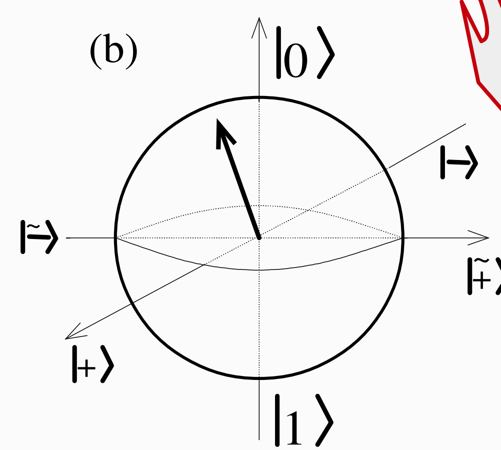
- Quantum bits may exist in **superpositions**

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$



$$|\psi\rangle = \cos\frac{\theta}{2}\,\mathrm{e}^{-i\phi/2}|0\rangle + \sin\frac{\theta}{2}\,\mathrm{e}^{i\phi/2}|1\rangle$$

electron/nuclear spin ½
two-level atom
photon polarization
Artificial atom ...



- What is strange with superpositions?
  - e.g. the superposition $|\pm\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
    represents both states at the same time
    in general many combinations depending on the phase ϕ
  - Dynamics (e.g. atomic clock)

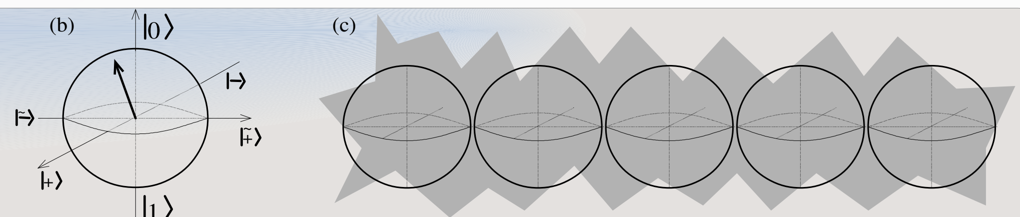
superposition for many qubits towards entanglement

- Composite system
  - Classical register: e.g. $0100110 \;\equiv\; |0100110\rangle = |\mathbf{x}\rangle$
  - **QM principle**: quantum states are **superpositions** of all classical "basis" states

$$|\psi\rangle = c_{\ldots 00}|\ldots 00\rangle + c_{\ldots 01}|\ldots 01\rangle + \cdots = \sum_{\mathbf{x}\in\{0,1\}^N} c_{\mathbf{x}}|\mathbf{x}\rangle$$

- N-qubit states: a great amount of information is needed to codify them (classically)
  - Projective Hilbert space $2 \times 2^N - 2$ real coefficients
  - coding a single qubit with M digits precision $I_1 \sim M \, \log_2 10 \times 2 \sim M$ bits
  - coding a N-qubit arbitrary (**entangled**) state $I_N \sim M \times 2^N$ bits **grows exponentially with N**
  - coding N independent (**factorized**) qubits $N \times I_1 \ll I_N$

- N qubits much more than separate parts : **entanglement**



Falci, Paladino – The Physics of Q-computation – Int. Jour Quant. Inf 2014

- **Feynmann**: due to entanglement **simulation of quantum systems** on classical computers is inefficient.
  - For instance codifying a system of N=100 spins would require $I_{100} \sim M \times 2^{100} \sim M \times 10^{30}$ bits a memory with linear dimensions $L \sim \underbrace{M^{1/3}}_{=10} \cdot 10^{10} \cdot \underbrace{1\,\mathrm{nm}}_{F} \approx 20\mathrm{m}$
  - N=350 spins would require $L \sim M^{1/3} \cdot 10^{39} \cdot 1\,\mathrm{nm} \approx 10^{30}\mathrm{m}$ > size of the Universe!

superpositions/entanglement → q-parallelism

- Classical computation: Turing machine computes functions

$$\begin{array}{lcl} 0000000 & \to & f(0000000) \\ \dots & & \\ 0100110 & \to & f(0100110) \\ \dots & & \end{array} \qquad \equiv |\mathbf{x}\rangle \to |f(\mathbf{x})\rangle \qquad \mathbf{x} \in \mathcal{B}^N, \quad \mathcal{B} = \{0,1\}$$

- Quantum computation
  - Start from a superposition

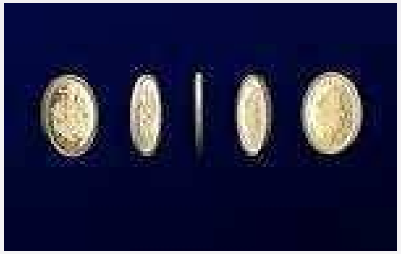
$$H^{\otimes N}|000\dots\rangle = \frac{1}{\sqrt{N!}}\left[|000000\rangle + \dots + |010011\rangle + \dots\right] = \sum_{\mathbf{x}} \frac{|\mathbf{x}\rangle}{\sqrt{N!}}$$

  - Linear evolution in Quantum Mechanics → **processing all inputs at once**

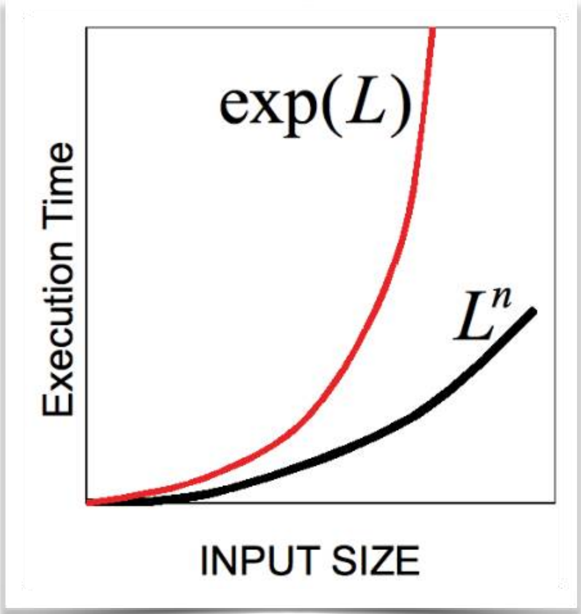
$$|\psi_0\rangle = \sum_{\mathbf{x}\in\mathcal{B}^N} |\mathbf{x}\rangle \otimes |0\rangle \to U_f|\psi_0\rangle = \sum_{\mathbf{x}\in\mathcal{B}^N} |\dots\rangle \otimes |f(\mathbf{x})\rangle$$

- Classical parallelism processes $\sim N$ inputs, while for a quantum computer they are $\sim 2^N$
  - May **quantum parallelism** help in performing tasks impossible on a classical computer?

q-parallelism → exponential speedup



- Deutch-Josza algorithm (1985)
  - Determining classically whether a coin is fair (head on one side, tail on the other) or fake (heads or tails on both sides) requires an examination of each side.
  - The analogous quantum procedure requires **just one examination step**



- For an N-qubit computer **quantum parallelism** promises $\sim 2^N$ **exponential speedup**

$$|\psi_0\rangle = \sum_{\mathbf{x}\in\mathcal{B}^N} |\mathbf{x}\rangle \otimes |0\rangle \rightarrow U_f|\psi_0\rangle = \sum_{\mathbf{x}\in\mathcal{B}^N} |\ldots\rangle \otimes |f(\mathbf{x})\rangle$$

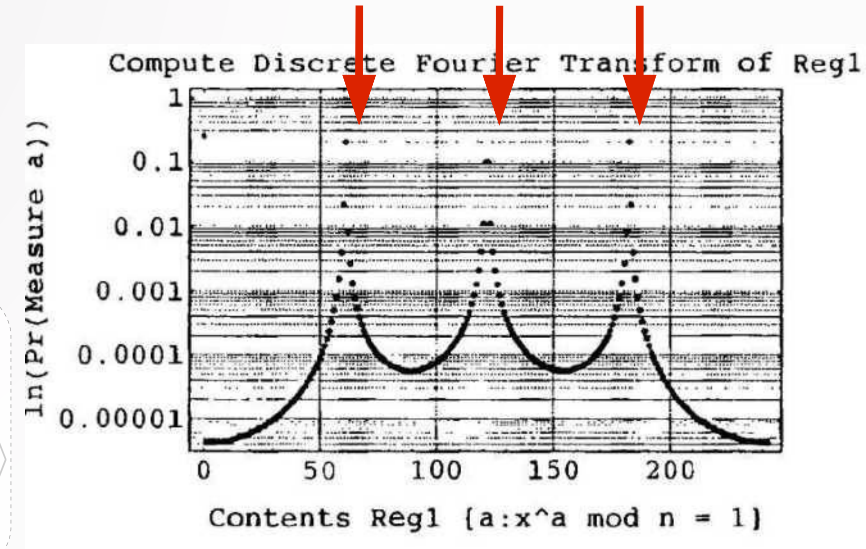
  which could turn certain algorithms from **exponentially hard (NP) to polynomial**

- **Wait**, not so simple: the ghost of **mesurement! Holevo bound**, a **no-go theorem** preventing information to be fully retrieved by quantum measurements

  Given N qubits, although they correspond a larger amount of (classical) information, the amount of classical information that can be retrieved, i.e. accessed, can be only up to N classical (non-quantum encoded) bits. This is surprising, in view of the large ”hidden” information ”lost” in a measurement.

measurement problem
q-parallelism is not enough

- How to bypass Holevo bound for measurement? Certaint tasks allow to do it
- Important example: **Shor's algorithm**
  - allows to find prime factors of a N digit ($\sim 2^N$ large number)
  - It would break the RSA Public Key Cryptographic Scheme
  - Description:
    - Define $f_{xn}(a) = x^a \,\mathrm{mod} n$
    - find period r of $f(a)$ → yields a prime factor of a
    - Calculate $|\psi_0\rangle = \frac{1}{\sqrt{q}} \sum_{q=0}^{q-1} |a\rangle|0\rangle \to U|\psi_0\rangle = \frac{1}{\sqrt{q}} \sum_{q=0}^{q-1} |a\rangle|f_{xn(a)}\rangle$
    - Calculate Quantum FFT and measure!!



© Williams Clearwater

4 220 851 x 2 594 209 → 10 949 769 651 859

ALWAYS EASY
(50 microseconds on a PC)

prime factors

10 949 769 651 859 → 4 220 851 x 2 594 209

HARD ON A CLASSICAL COMPUTER
(1 second on a PC)

For 250 digits, a million years!

"number field sieve"
super-polynomial
$\exp[\alpha N^{1/3} (\ln N)^{2/3}]$

EASY ON A QUANTUM COMPUTER
~ 100 000 qubits, ~ a few hours

polynomial time

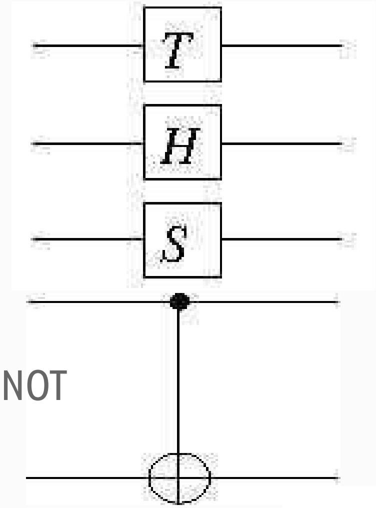
© M. Devoret

Modestly sized QC's **exponentially outperform** the most powerful Cl-C in solving some specific problem.

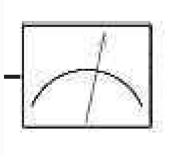
efficiency, robustness, QEC → "quantum supremacy"

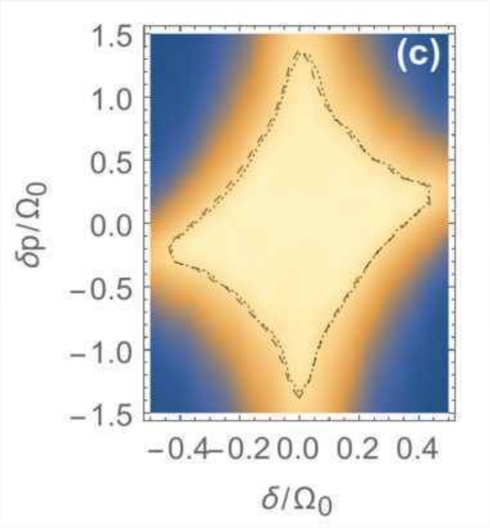
- **Quantum supremacy**
  performing tasks that classical computers cannot perform efficiently

- **Universality construction**:
  all transformations in the LARGE ($\mathrm{SU}(2^N) \gg \mathrm{SU}(2^{\otimes N})$) Hilbert space can be decomposed in a sequence of "quantum gates" from a universal set (H,S;T,CNOT) acting on one or at most two qubits



Individual qubit measurement





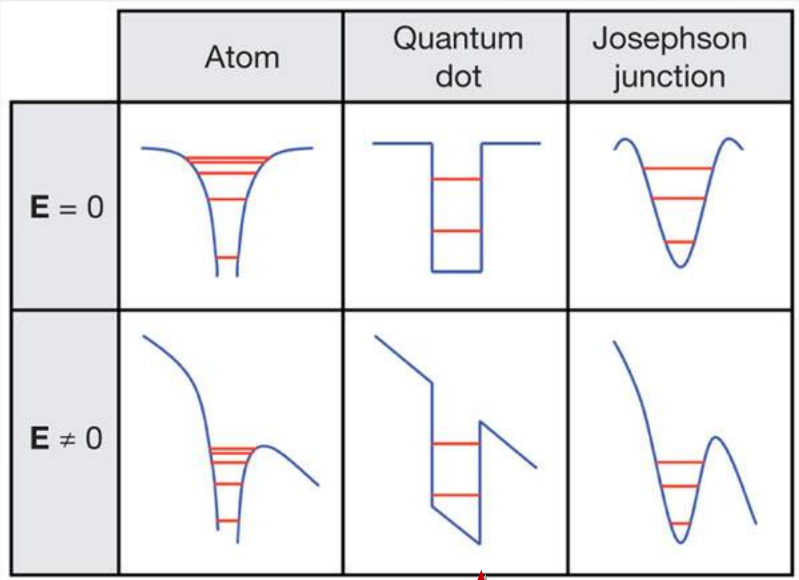
- Requires **robustness against fluctuations** of the control fields

Three-level Three-photon scheme for adiabatic coherent state transfer
P. G. Di Stefano, E. Paladino, T. J. Pope, G. Falci, PRA (2016)

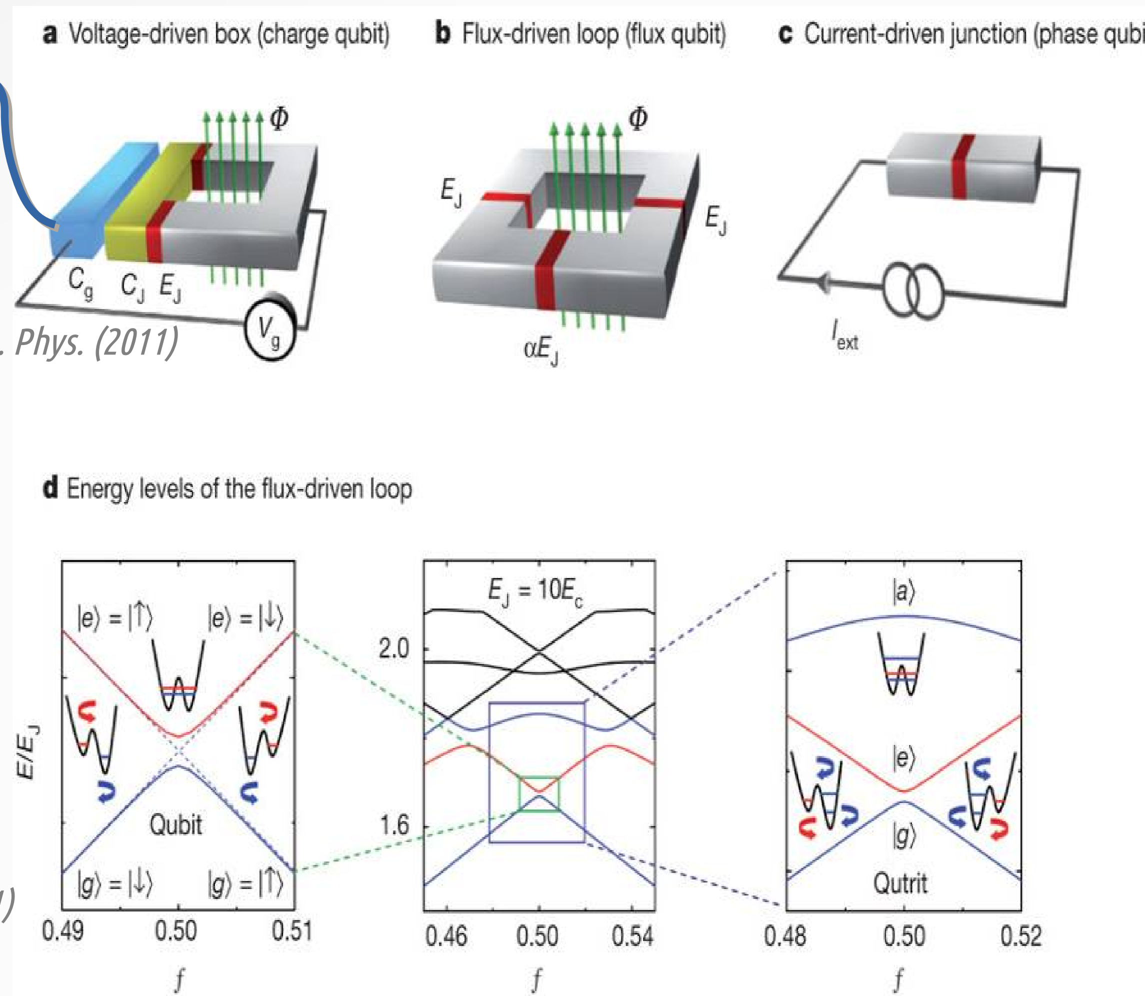
- Errors due to **markovian decoherence** or imperfect control can be controlled thanks to the existence of **Quantum Error Correction (QEC) threshold theorems**:
  1 error over $10^4 - 10^5$ gates can be corrected by QEC passes and computation can proceed indefinitely

artificial atoms

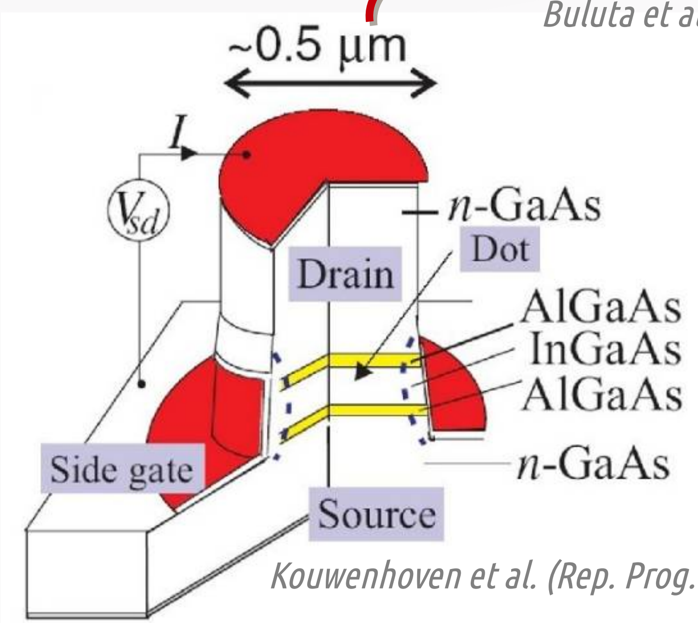
semiconductor or superconductor based nanodevices



- artificial atoms are solid state nanodevices with functionality of atoms
- **Two major design “platforms”**
  - Semiconductor-based (qdot, qwells)
  - Superconductor-based (Josephson circuits)



Buluta et al. Rep. Prog. Phys. (2011)



Kouwenhoven et al. (Rep. Prog. Phys. (2001)

Incoherent ↔ coherent behavior
the roadmap from/to the macroscopic world

- Single atom more performing than a classical bit.
  But classical bits are quantum mechanical objects. How comes that their potentiality as quantum processors fades away?
  The state variable is a collective variable interacting with many uncontrolled degrees of freedom → **Decoherence**

Matter (electrons)

top-down ↓ / bottom-up ↑

macroscopic

Semiclassical
particle-like electrons in lattices
only EMERGENT quantum properties
(binding, Pauli)
bulk solids (microelectronics)

~100 nm

mesoscopic

Quantization **(energy, charge)**
still particle-like electrons

Incoherent nanosystems
(nanoelectronics)
quantum dots, wires, wells
single electronics, spintronics
molecular electronics

~1 nm

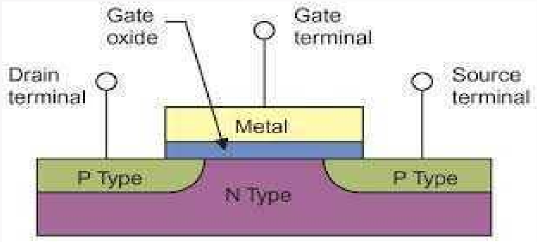
microscopic

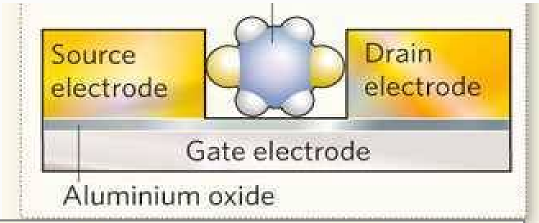
Coherence
wave-like electrons
coherent nanostructures
ballistic conductors

NMR

molecular and atomic systems

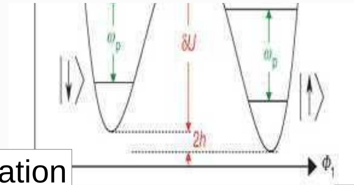
Semiclassical



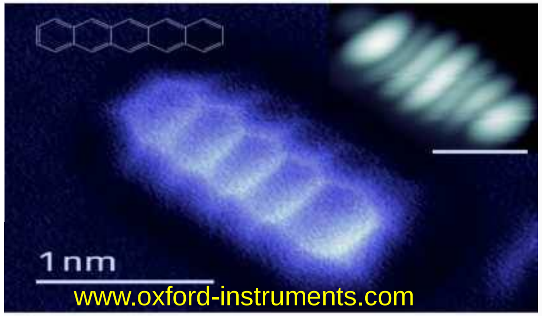


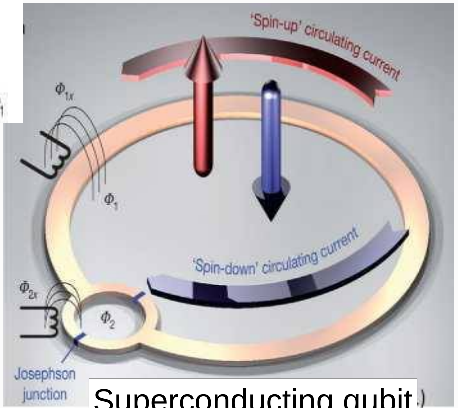
Molecular SET Transistor - Song et al., Nature (2009)

Quantum incoherent



quantum computation & communication





Superconducting qubit
Nature 2011

decoherence
and the macroscopic world

- Single atom more performing than a classical bit.
  But classical bits are quantum mechanical objects. How comes that their potentiality as quantum processors fades away?
  The state variable is a collective variable interacting with many uncontrolled degrees of freedom → **Decoherence**

Matter (electrons,atoms) | **Light**

top-down ↓ | bottom-up ↑

macroscopic

Semiclassical
particle-like electrons in lattices
only EMERGENT quantum properties
(binding, Pauli)
bulk solids (microelectronics)

Classical wave
Incoherent light
Coherent SEMIclass. fields (Laser)

Semiclassical

~100 nm

mesoscopic

Quantization **(energy, charge)**
still particle-like electrons
Incoherent nanosystems
(nanoelectronics)
quantum dots, wires, wells
single electronics, spintronics
molecular electronics

Quantized photon number
(particle-like properties)
(single) photon-matter interaction
absorption-emission

Quantum incoherent

"There is plenty of room at the bottom" 1959

"Simulating Physics with computers" 1982

Coherence
wave-like electrons
coherent nanostructures
ballistic conductors

~1 nm

microscopic

NMR

molecular and atomic systems

Quantum Technologies

Single photon control
(manipulation, generation/detection)
quantum optical systems

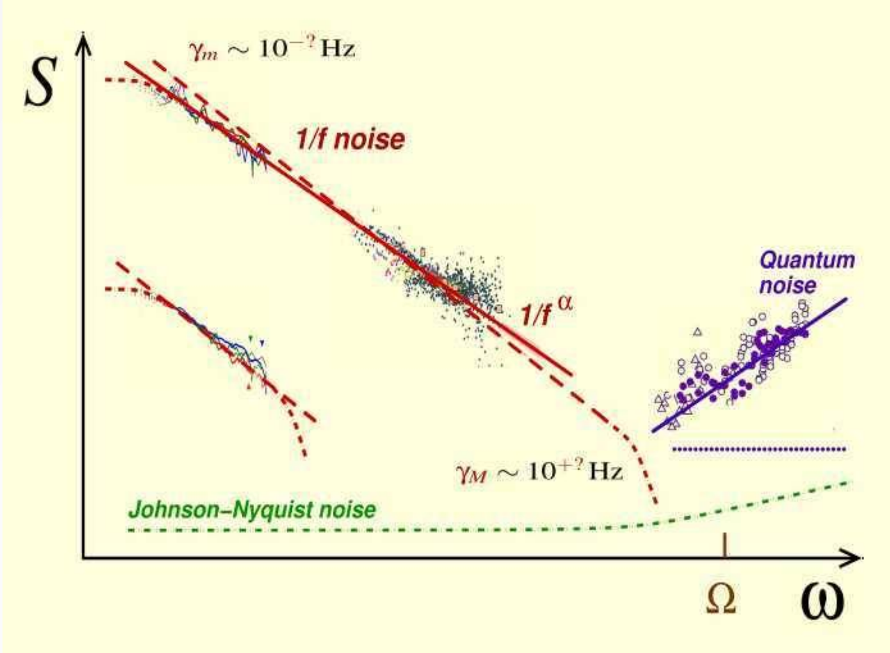
Quantum coherent

understanding decoherence in AAs

- **Decoherence** due to an environment of uncontrolled degrees of freedom.

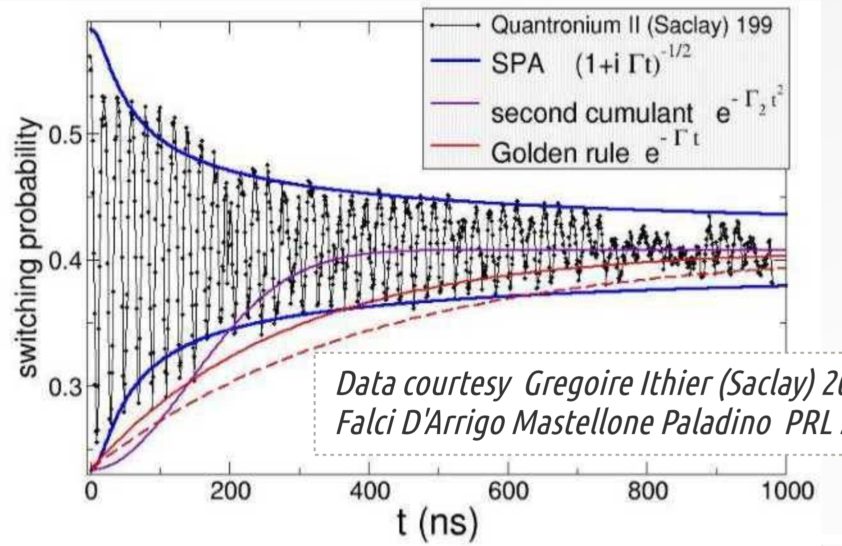
  Backrgound charges, stray magnetic flux, critical current noise, dielectric losses, nuclear spins...

  → We deal with an **open (bipartite) quantum syste**

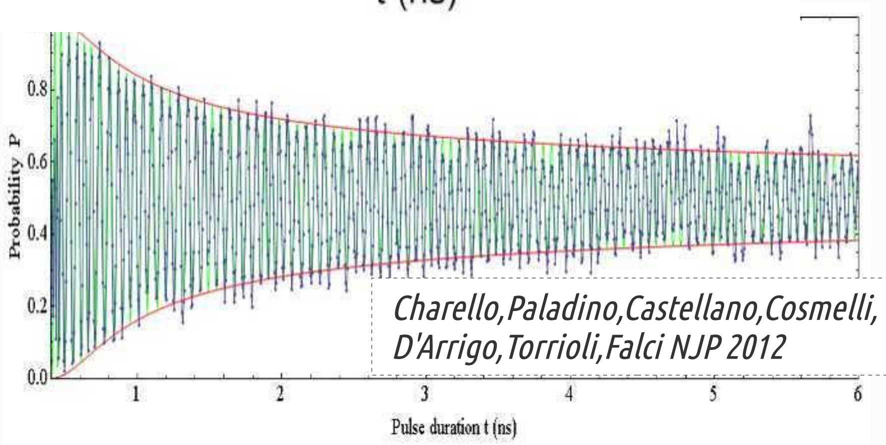


- broad band colored **noise**: **low-frequency (1/f)** and **high-frequency (quantum)**

  Paladino, Galperin, Falci, Altshuler, Review Modern Physics (2014)



Data courtesy Gregoire Ithier (Saclay) 2004
Falci D'Arrigo Mastellone Paladino PRL 2005



Charello,Paladino,Castellano,Cosmelli, D'Arrigo,Torrioli,Falci NJP 2012

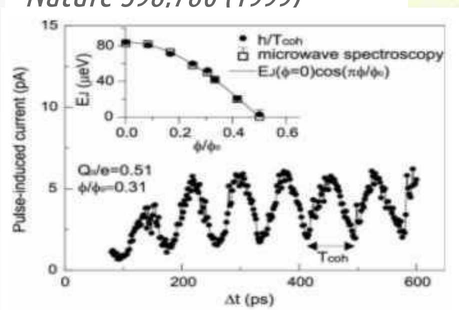
- Recipes for **noise protected** qubits
  - **Design** – suitable ***H bandstructure*** & working at **symmetry points** suppresses low-frequency dominant noise → increase dephasing times
  - **Control** – Oprate active protection strategies as ***dynamical decoupling*** shining pulse sequences which dynamically average the environment
  - **New materisls** (sapphire substrates)

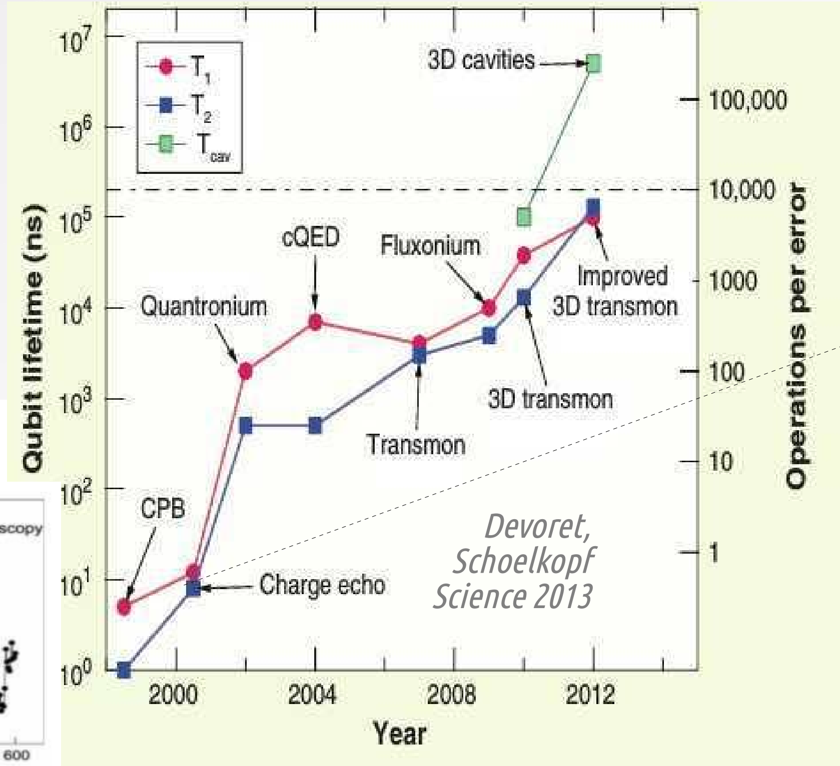
fighting decoherence & upscaling

- figures **tremendously improved** in the last few years

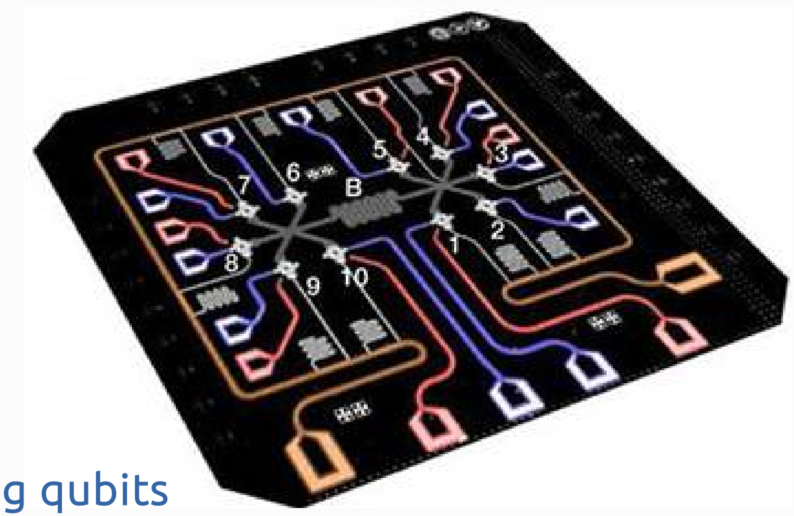
- Recipes for **noise protected** qubits
  - **Design, Control, New materisls**

Nakamura, Pashkin, Tsai, Nature 398.786 (1999)





"Moore Law" trend

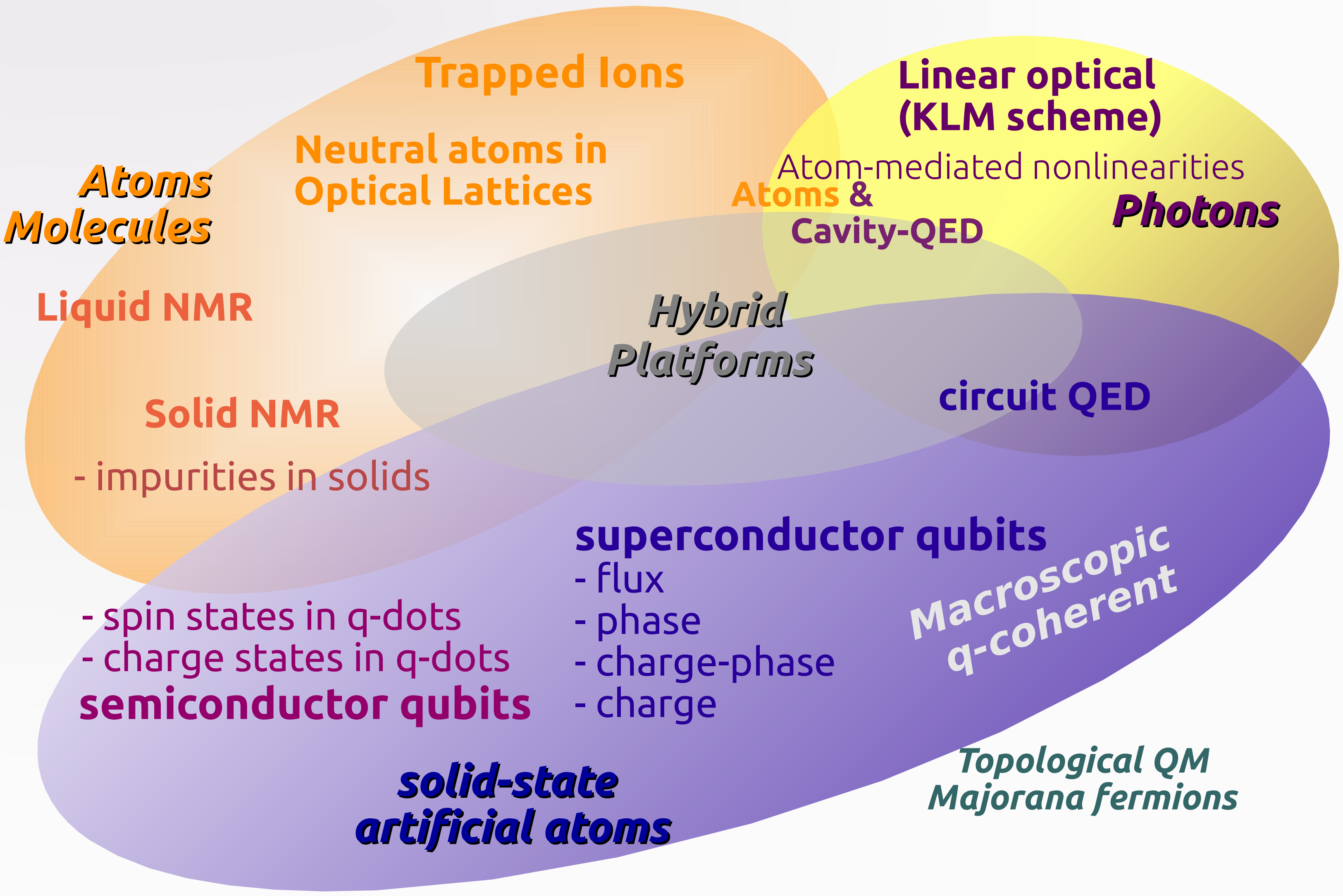


- **Upscaling –** 10 superconducting qubits

  J-W Pan, University of Science and Technology of China 13/4/2017

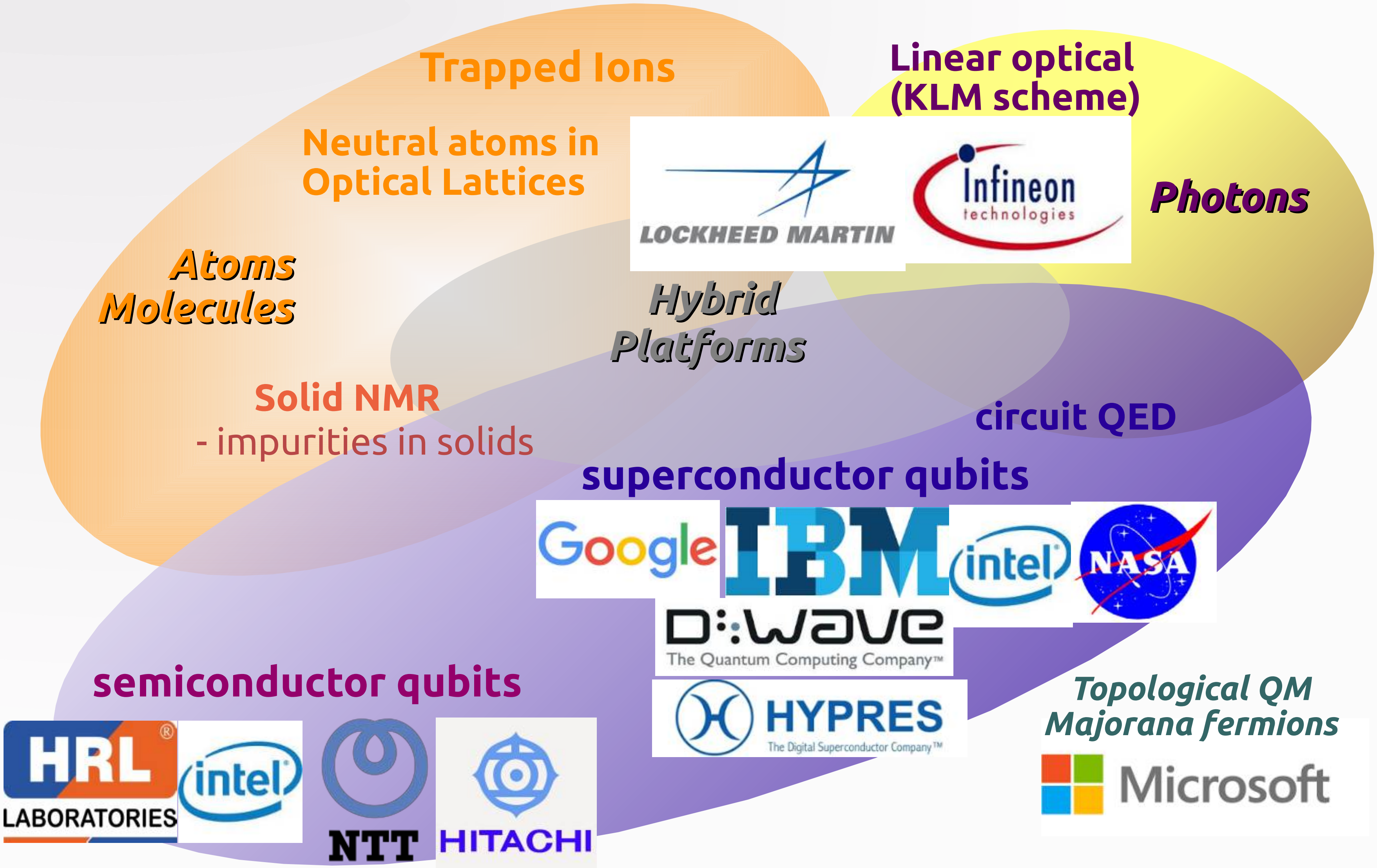
  - 10 qubits, each half a millimetre across and made from slivers of aluminium, are arranged in a circle around a a bus resonator.
  - Early proposal of operation with superconducting quantum bus (*Plastina, Falci PRB 2003*) & new proposal with virtual quantum bus (*Falci et al. Fort. Phys. 2017)*

current implementations of qubits



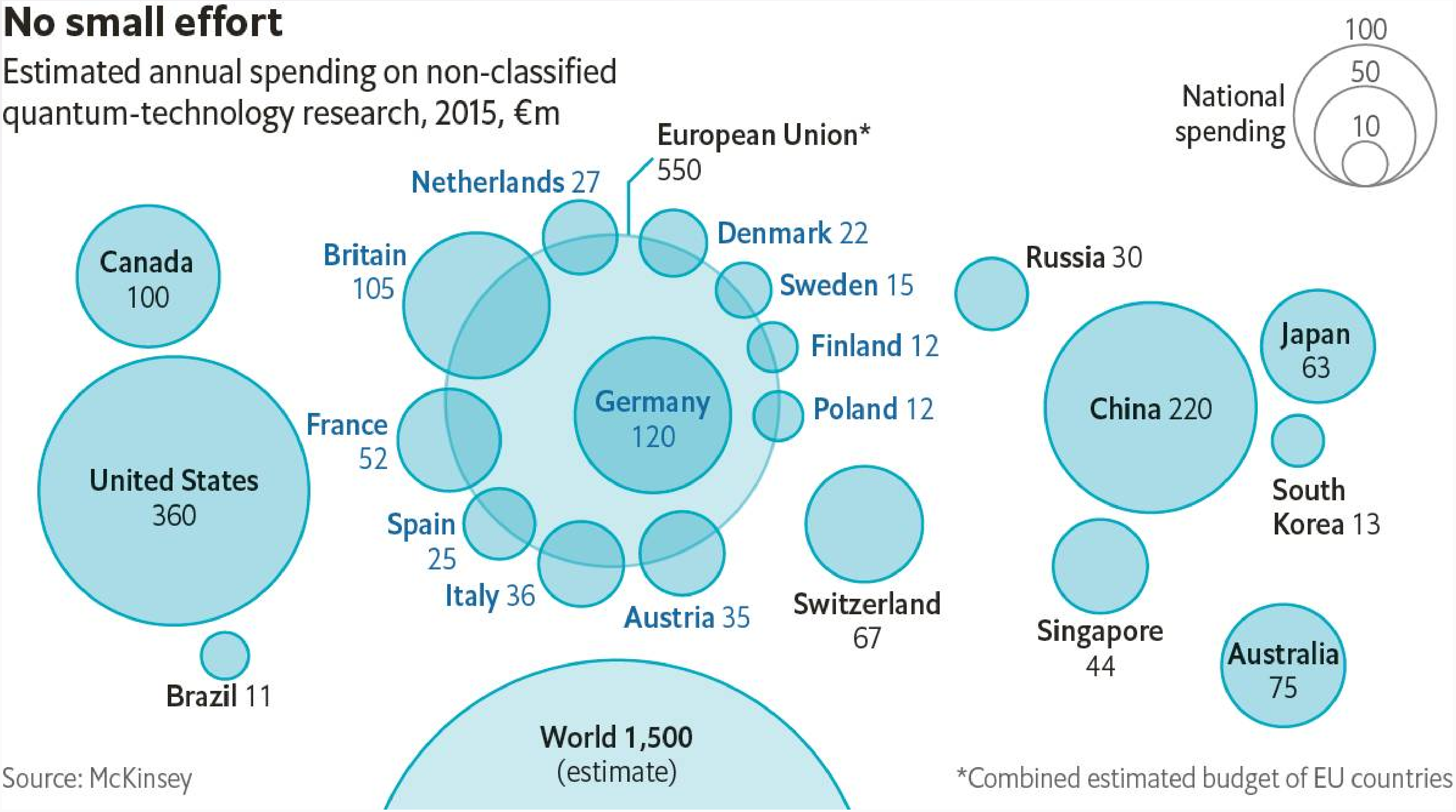
- Forefront runners for digital computers: ion traps & superconductors
- Main outsiders: cold atoms, hybrid photon/impurity systems
- High risk high pay off: topological systems

industry wolrdwide has entered the game



public research funding worldwide in 2015

- Top 8 nations: USA, China, Germany, UK, Canada, Australia, Switzerland, Japan



http://www.economist.com/technology-quarterly/2017-03-09/quantum-devices

EU answer

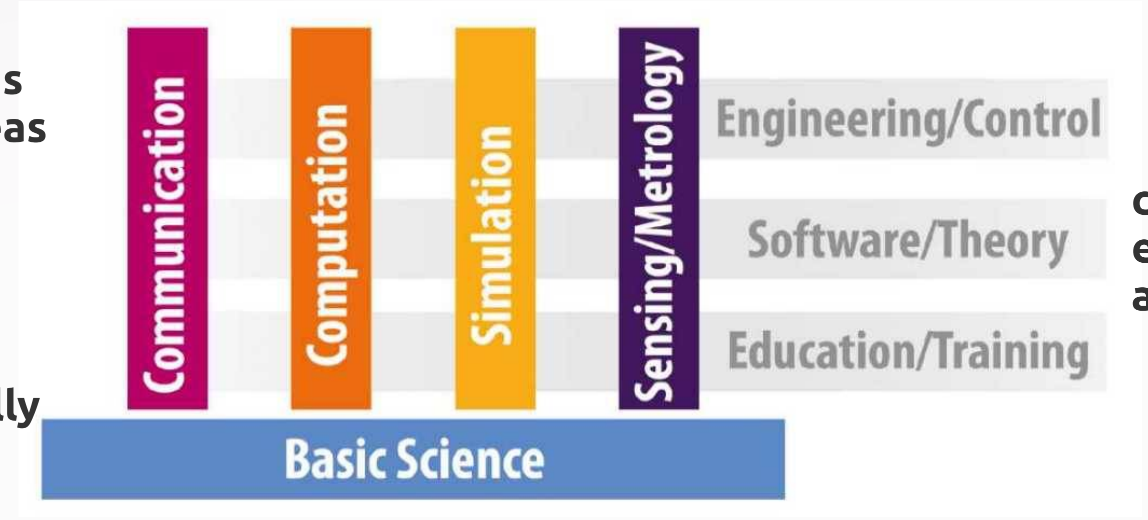
FET-Flagship on Quantum Technologies 2018-28

- Le Future & Emerging Technologies ("FET") Flagships sono **iniziative su vasta scala di ricerca e innovazione “science-driven”**, che affrontano sfide scientifiche e tecnologiche interdisciplinari.
  - ec.europa.eu/digital-single-market/en/fet-flagships
  - 2013: le prime Flagship: *Graphene* (youtu.be/aKcQMfi3tzg) e *Human Brain* (youtu.be/I5HaiMXANhA)

- 17/05/2016 – **annuncio la Flagship su QU-TE**
  - Durata **2018-2028** – **Finanziamento 1 G€** (50% UE + 50% investimenti di Stati/Regioni Membri)
  - Strategic Research agenda: supports **R&D** activities on **four major applied domains (pillars)** and Basic Science as a **cross-cutting domain**

4 vertical domains → application areas

1 domain horizontally fully cross-cutting



common enabling aspects

- **Job opportunities in Europe for academic and industrial research in the next 10 years**

quantum simulation

"...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...and I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

R. P. Feynman, 1965 Nobel laureate
Simulating physics with computers, Int. J. Theor. Phys. 21, 467 (1982)

- Quantum simulators will allow to **simulate materials or chemical compounds**, as well as to solve equations in other areas, from high-energy physics to biology.
- They are **simpler to build** than all-purpose quantum computers (~100 qubits already OK)
  50 qubits enough to demonstrate quantum supremacy
- Platforms: ultracold atoms in optical lattices, trapped ions, arrays of superconducting qubits or of quantum dots and photons.

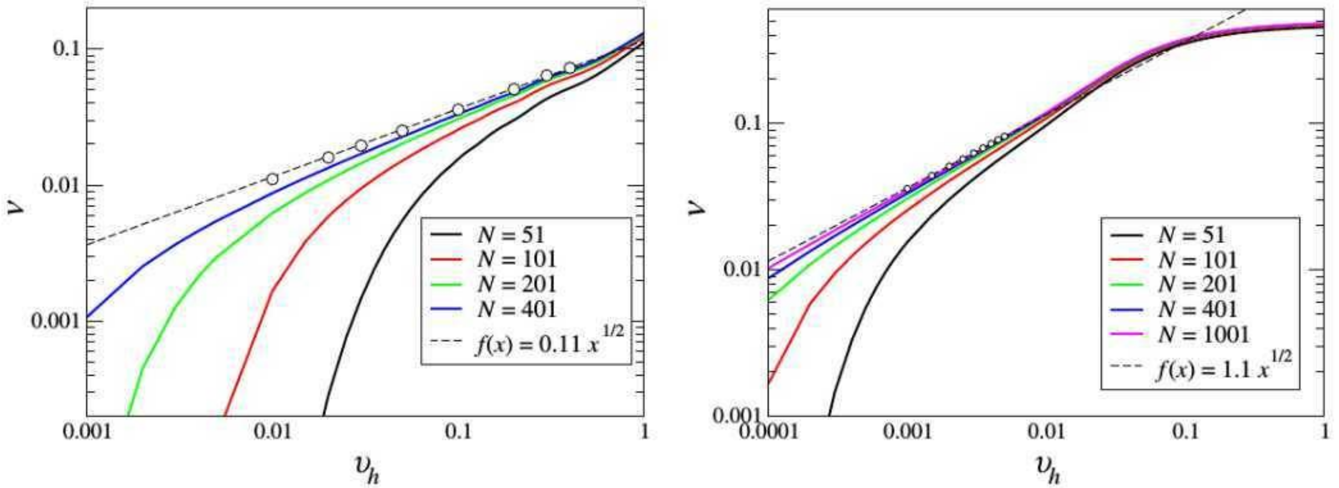
Platforms for quantum simulation; development of new measurement and control techniques and of strategies for the verification of quantum simulations.

Application of quantum simulations to condensed matter, chemistry, thermodynamics, biology, high-energy physics, quantum field theories, quantum gravity, cosmology and other fields.

QUANTERA
ERA-NET Cofund in Quantum Technologies

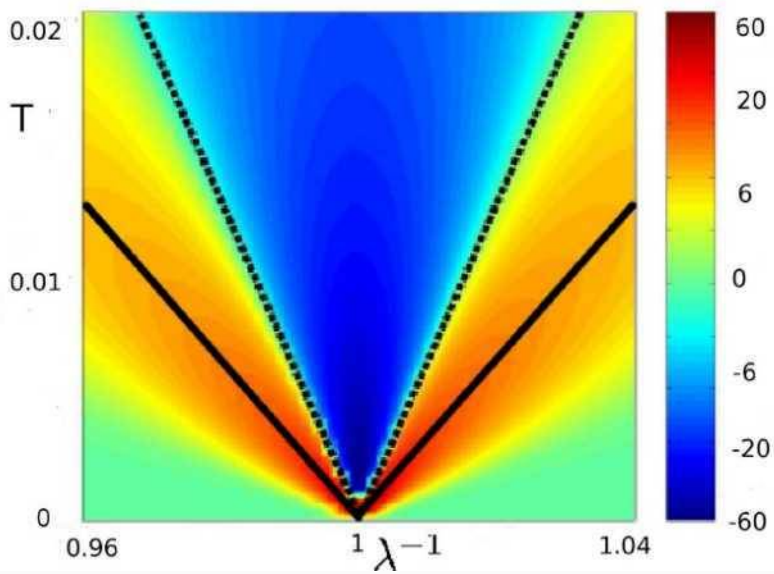
- First prototypes (**D-wave annealer**) provide simulations beyond current supercomputers for some particular problems. **Available on-line (by Google & NASA) within 2017.**

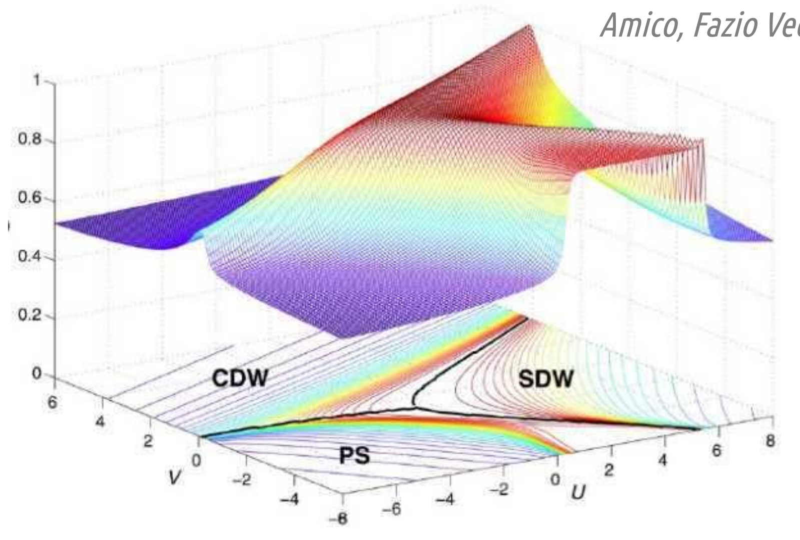
quantum critical systems
entanglement and dynamics



Fubini, Osterloh, Falci (2007) NJP

Figure 4. Left panel: excitation density versus v_h at $\gamma = 1$. The full circles represent the extrapolated $N \to \infty$ values and the dashed line is the best fit of those points. Right panel: the same as in the left panel, but with $\gamma = 0.1$.





Amico, Fazio Vedral (2008) RMP

central message mysteries of QM at the heart quantum technologies

- **Maximum failures** of QM in satisfying common sense
  → become **resources** for genuinely quantum technologies

- **Superposition & entanglement**
  → allow for **exponential parallelism** in computation

↕

- **Non-separability & non-locality**
  → allow new astonishing protocols of quantum **communication**

- **Quantum measurement (collapse)**
  → allows **secure** communication, protected by laws of nature

- **Macroscopic quantum objects (as Schrodinger cats)**
  → build a macroscopic object whose many degrees of freedom are controllable and exhibit **quantum behavior on a macroscopic scale**

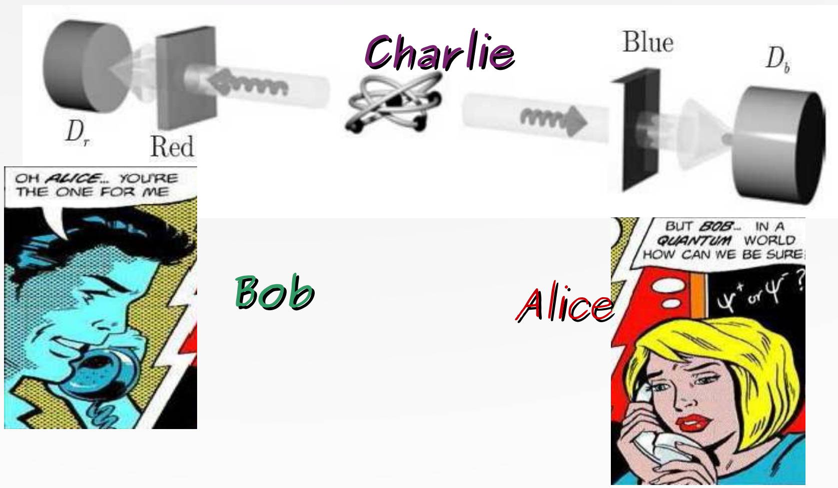
bipartite quantum systems

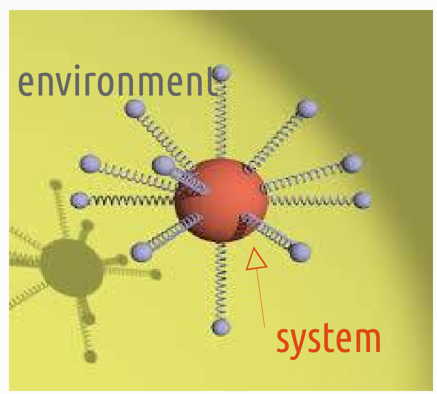
Haroche-Raimond §2.4
Appunti, §3
Nazarov-Danon §1

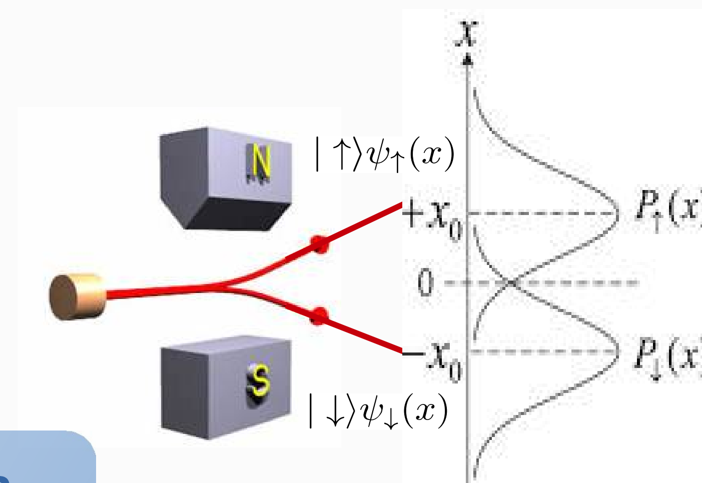
- a new peculiar feature of quantum coherence: superposition principle applied to composite systems → **entanglement**

$$|\Phi^{\pm}\rangle = \frac{|00\rangle \pm |11\rangle}{\sqrt{2}} \; ; \; |\Psi^{\pm}\rangle = \frac{|01\rangle \pm |10\rangle}{\sqrt{2}}$$

- bipartite system are a **paradigm** for
  - **quantum communication**: Alice and Bob share **entangled** pairs
  - **open systems**: principal system + environment **entanglement** → **decoherence**
  - (pre) **measurement theory**: system-meter **entanglement**







- mathematically: a subsystem **cannot be described by a pure state**, but only statistically via **a density operator** ρ^A

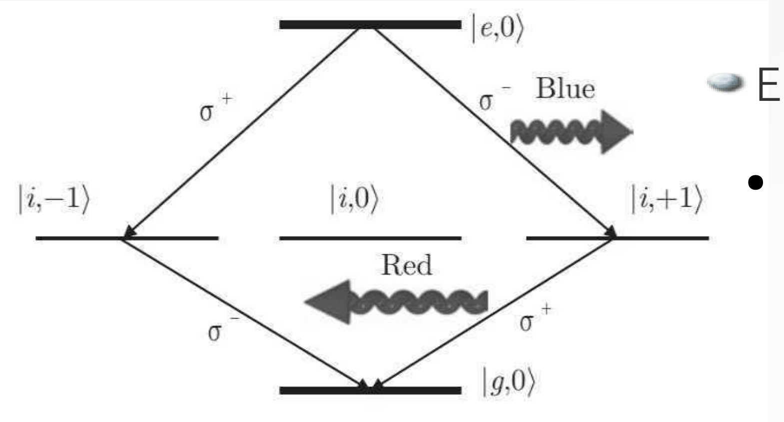
product & entangled states

Haroche-Raimond §2.4
Appunti, §3
Nazarov-Danon §1
Nielsen Chuang – 7.4.1

- Examples
  - Factorized states : describe statisically independent systems $|\Psi\rangle = |\psi\rangle|\phi\rangle$
  - "maximally entangled" Bell states $|\Phi^{\pm}\rangle = \frac{|00\rangle \pm |11\rangle}{\sqrt{2}}$; $|\Psi^{\pm}\rangle = \frac{|01\rangle \pm |10\rangle}{\sqrt{2}}$
  - "complicated" states may be factorized $\frac{1}{2}[|00\rangle \pm |01\rangle \pm |10\rangle + |11\rangle] = \frac{|0\rangle \pm |1\rangle}{\sqrt{2}} \otimes \frac{|1\rangle \pm |0\rangle}{\sqrt{2}}$

pure states are said **entangled** when they **cannot be factorized**

- difficult to test



- Entangled pair production
  - E.g. photons from atomic cascade (circ. pol.) → Bell state

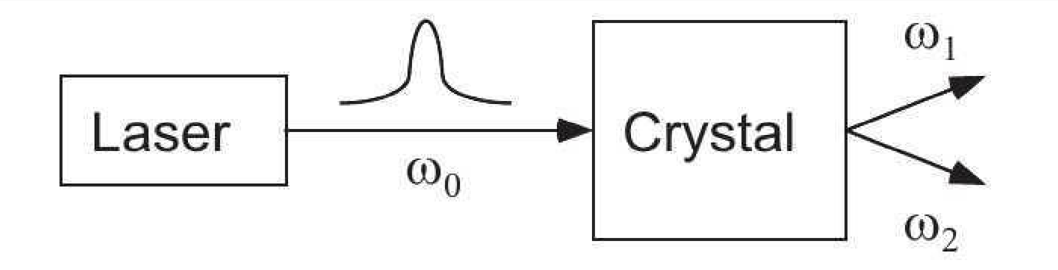
$$|\Psi^{+}\rangle = \frac{|HV\rangle + |VH\rangle}{\sqrt{2}} = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

if we measure one photon polarization, the other is determined

- E.g. photons from down conversion

  → singlet Bell state

$$|\Psi^{-}\rangle = \frac{|HV\rangle - |VH\rangle}{\sqrt{2}} = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$



entanglement and correlations I

- Correlations in Bell states

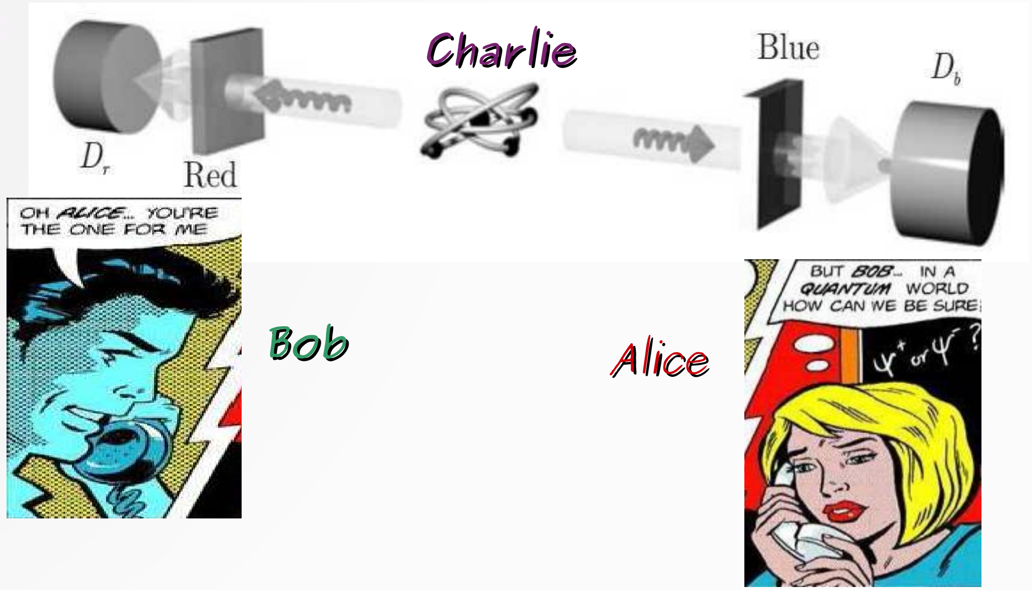
$$|\Psi^-\rangle = \frac{|HV\rangle + |VH\rangle}{\sqrt{2}} = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

if we measure one photon polarization, the other one is determined

- **What's special?**

also classical correlations do the job

$$\rho = \frac{1}{2}|01\rangle\langle 01| + \frac{1}{2}|10\rangle\langle 10|$$



- **However correlations** in $\dfrac{|01\rangle - |10\rangle}{\sqrt{2}} = e^{i\alpha}\dfrac{|+-\rangle - |-+\rangle}{\sqrt{2}}$ **are much stronger:**

no matter which axis is chosen for the measurement of the first polarization, **that choice determines what happens to the other**.

- **Moreover**: the outcome of the first measurement is fully undetermined in whatever basis we measure (i.e. for whatever observable we measure) → **individual subsystems do not possess separate identities:** in QM we may have **complete knowledge of a system as a whole** (state vector) **and still know nothing about its parts**.
  - Two classical particles possess individually positions and momenta, and if they do not interact, measurement on one of them does not affect measurement on the other.
  - On the contrary In QM we may have complete knowledge of a system as a whole (the state vector) and still know nothing about it

entanglement and correlations II

- Strange properties of Bell states:
  - **No matter which axis** is chosen for the measurement of the first polarization, **that choice determines what happens to the other**.
  - The outcome of the first measurement is fully undetermined in whatever basis **individual subsystems do not possess separate identities**

- This has lead to the formulation of the **paradox by EPR** which were unconfortable with:
  - The fact that photons seem to **know about each other instantaneously**
  - Even stranger, this mutual knowledge holds even if the polarization axis for our measurement is not chosen until after the photons have flown considerable distance apart, defiyig apparently special relativity **("spooky action at distance")**

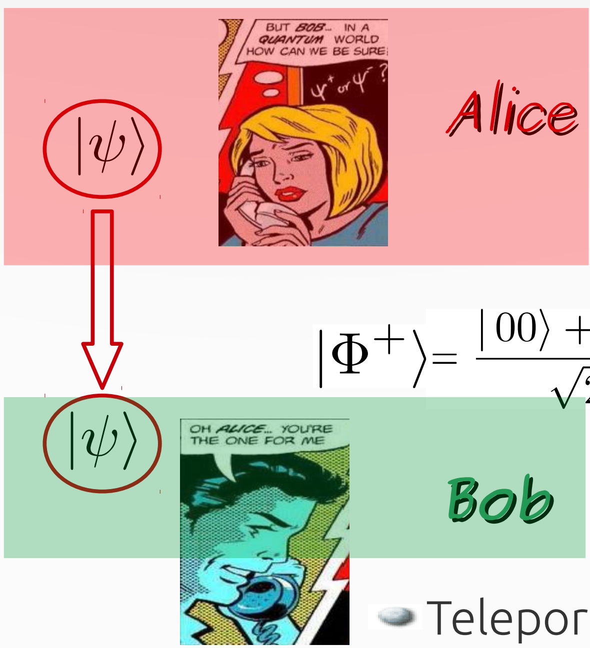
- **Bell-like experiments** have shown that bipartite quantum systems possess **correlations**
  - ''much stronger than classical ones``
  - **"non local"** they apparently set in also for spatial separation preventing interaction
  - **Can be used as a resource in quantum communication and cryptography**, besides quantum computation (q-parallelism)

applications to q-communication

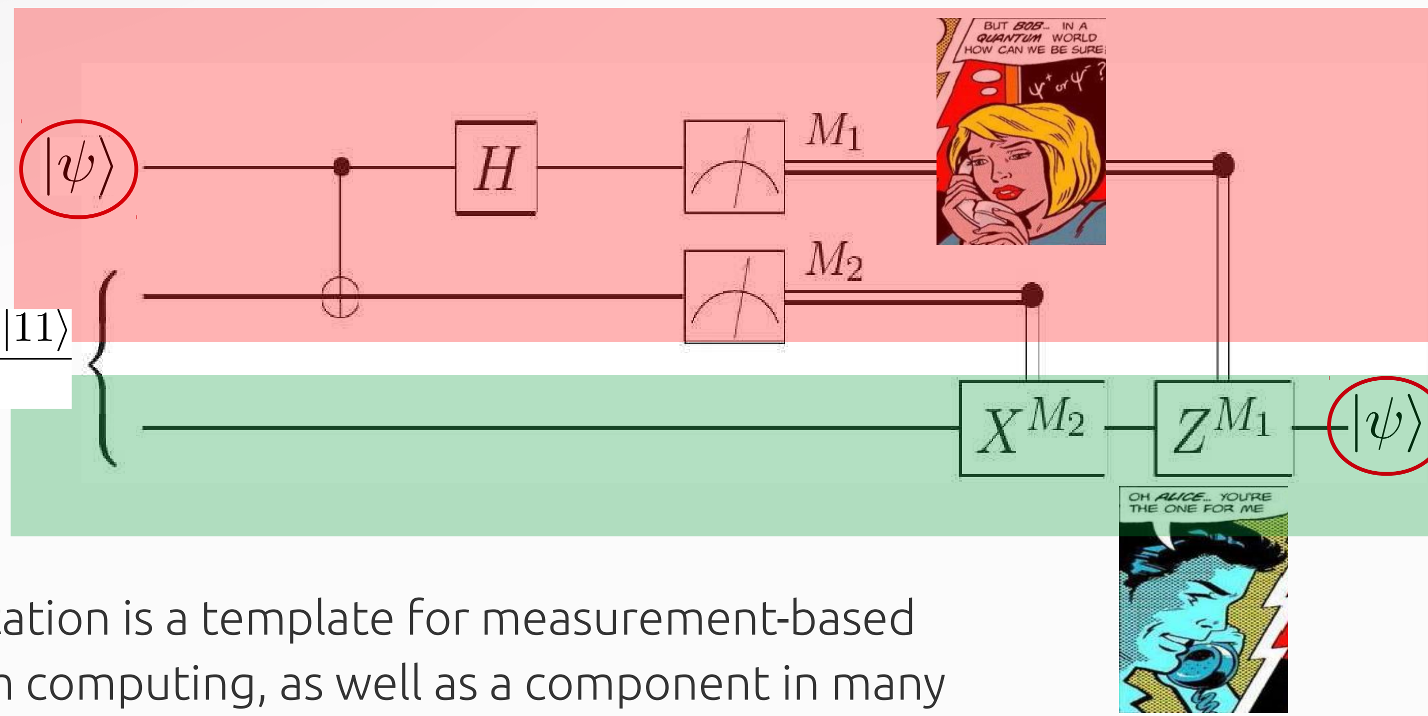
- **Great!** we now use entanglement to communicate at large distance at superluminal speed!
  - Not at all! It is **impossible to send a signal** using only "instantaneous" Bell correlations.
  - Let's play a trick: we perform a quantum tomography on copies of the second photon

    Forbidden by **NO cloning theorem** $\nexists U \;:\; U|\psi\rangle|0\rangle = |\psi\rangle|\psi\rangle \quad \forall|\psi\rangle$

- **But:** to send an unknown quantum state $|\psi\rangle$ to Bob, should Alice prepare many identical qubits and send each of them? **NO: Quantum Teleportation protocol**



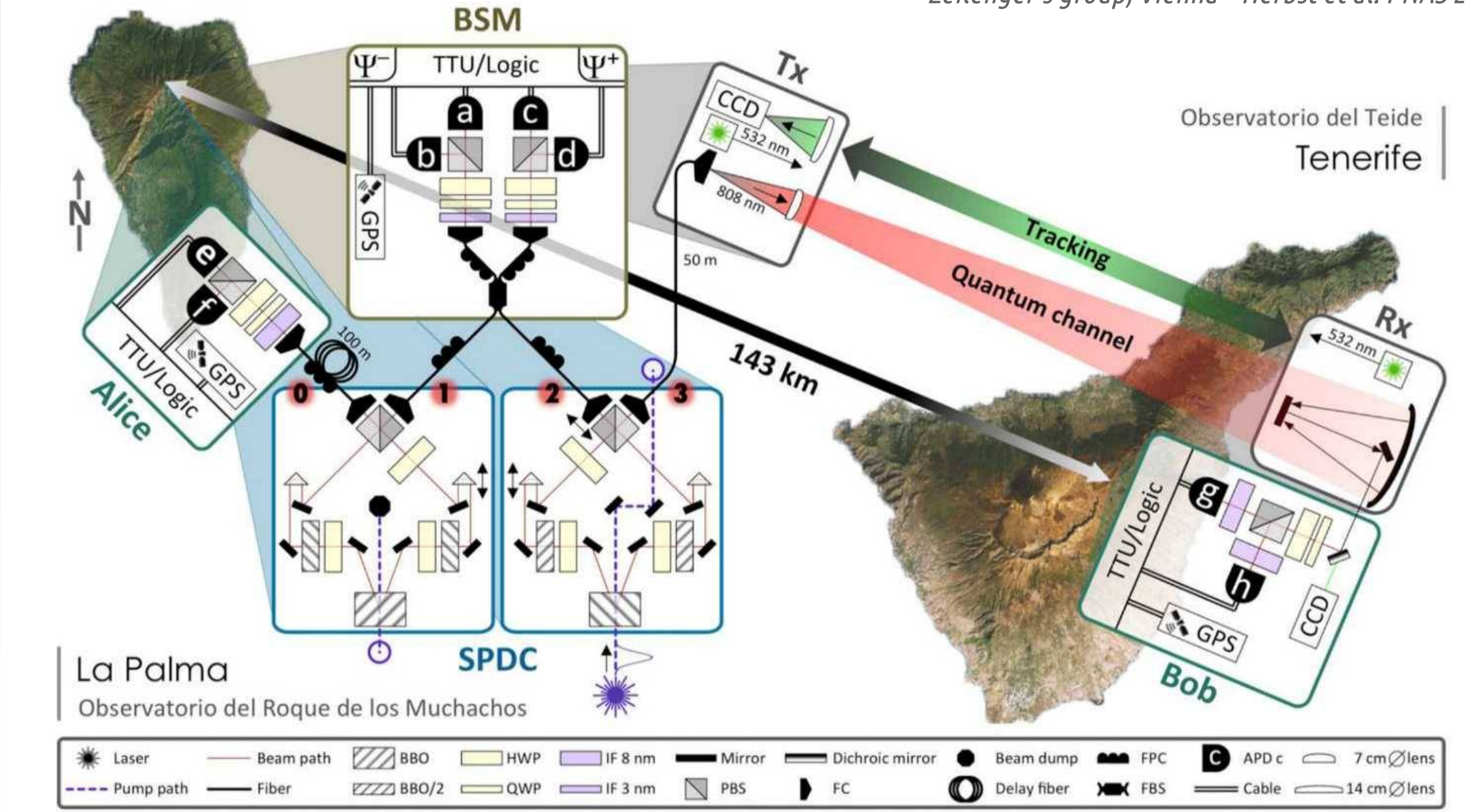
$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$



- Teleportation is a template for measurement-based quantum computing, as well as a component in many communication protocols.

teleportation of entanglement over 143 km

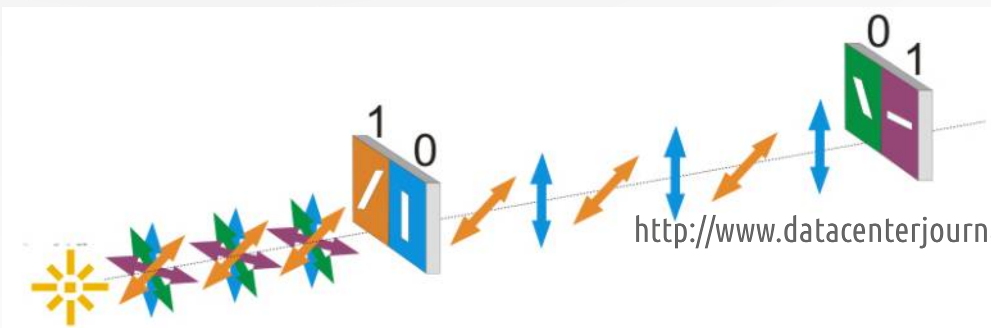
Zeilenger's group, Vienna – Herbst et al. PNAS 2014



and Alice, were situated on La Palma and Bob on Tenerife. The two SPDC sources generated the entangled photon pairs "0-1" and "2-3." Photons "1" and "2" (photons are indicated by black numbers on red circles) were subjected to a BSM. A 100-m fiber delayed photon "0" with respect to photon "3," such that Alice's and Bob's measurements were space-like separated. Revealing entanglement of photons "0" and "3" between Alice and Bob verified successful entanglement swapping. Polarization-entangled photon pairs $|\Psi^-\rangle_{01}$ and $|\Psi^-\rangle_{23}$ were generated in two identical sources via SPDC in a nonlinear BBO crystal. The photons were then coupled into SM fibers with fiber couplers. Any polarization rotation in the SM fibers was compensated for by fiber polarization controllers. Photons "1" and "2" were spectrally filtered with interference filters (IFs) with a full width at half maximum (FWHM) of 3 nm and overlapped in an FBS. A subsequent polarization-dependent measurement was performed, using a quarter-wave plate (QWP), a half-wave plate (HWP), a PBS, and four APDs (a, b, c, and d) in the BSM. Photon "3" was guided via a 50-m fiber to the transmitter (Tx) and sent to Bob in Tenerife, whereas photon "0" was delayed by a 100-m fiber before its polarization detection at Alice. The receiver (Rx) on Tenerife captured photon "3" where Bob performed his polarization-dependent measurement. Both Alice and Bob spectrally filtered their photons with IFs with 8-nm FWHM. All detection events were time stamped by TTU with a resolution of 156 ps and stored for subsequent analysis. See the text for further details.

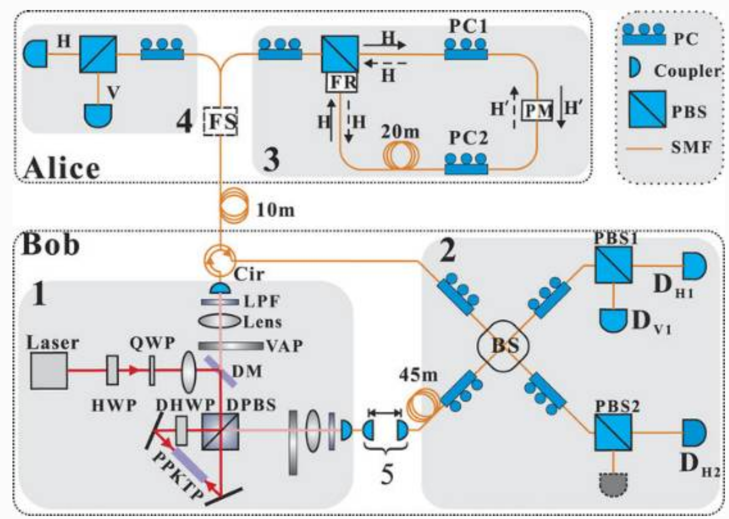
quantum cryptography

- Private key cryptosystem – A and B share a cryptographic key used for encryption (A) and decryption
  - Eavesdropping the private key (cloning)
- Public key cryptosystem
  - A key easy to apply (encryption) but difficult to invert (decryption)
  - B makes available to everybody the public key but only him possesses the secret key making the inversion easy.
  - Rivest, Shamir, Adelman (RSA) cryptosystem based on factoring: Shor's factorig algorithm may break RSA with



http://www.datacenterjournal.com/

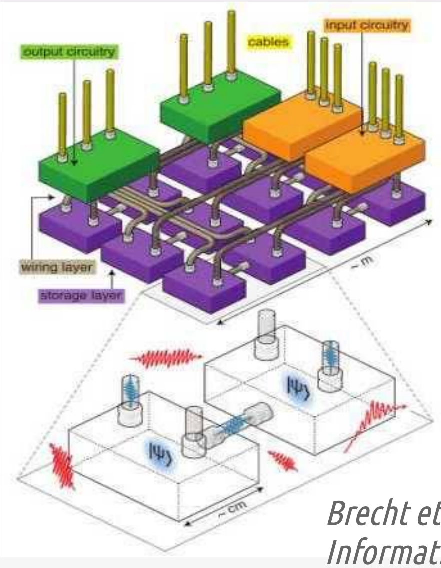
- Quantum cryptography – private quantum key distribution (QKD): Bennett & Brassard, BB84
  - Observation disturbs the physical system (no cloning)
  - Bob can understand if there is a disturbance and throw away the corrupted qubits of the private key, extablishing new ones
  - **Secure communication guaranteed by nature**



- Entanglement-based protocols Ekert 91 and Ping-Pong

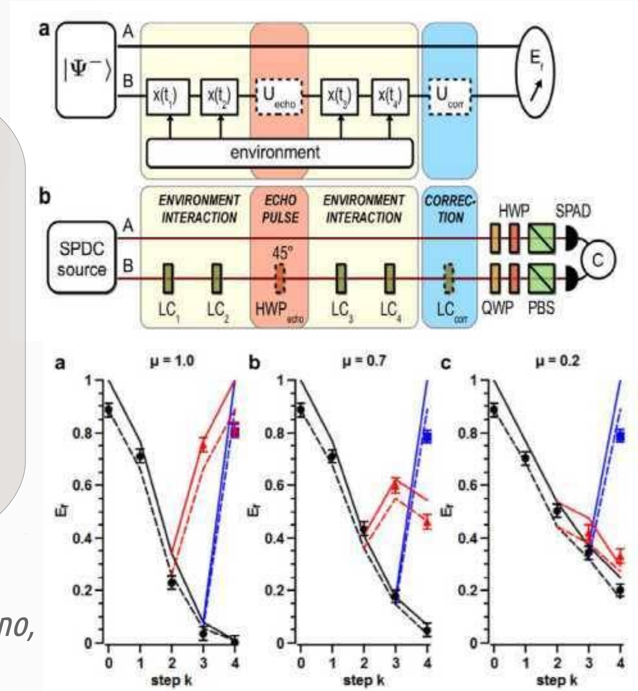
Chen et al. Sci. Repts 2016

some strategic direction



Brecht et al., npj Quantum Information (2016)

- **Quantum architectures**
  (2 → few qubits; circuit QED; all optical systems distributed quantum networks)
  - How to generalize passive and active stabilization
  - Scaling of resources ?
    Favorable for Markovian noise + QEC
    → . Non-Markovian noise?



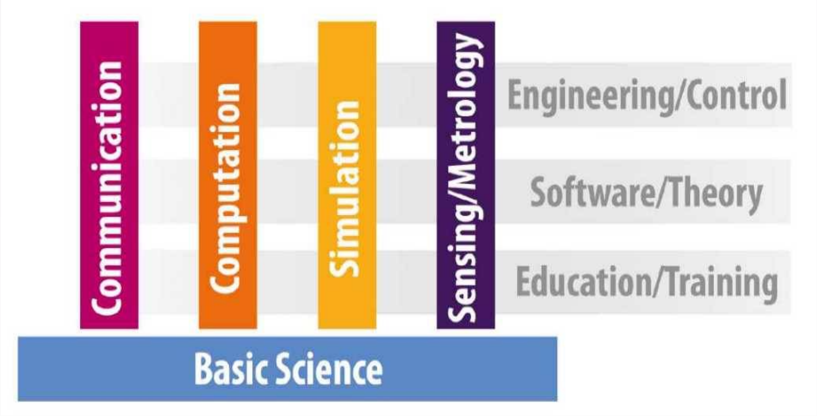
Orieux,, D'Arrigo,, …., Paladino, Falci, Mataloni, Sci rep 2015

- **Quantum Sensors –** exploring superconductivity and quantum control to implement coherent noise detection: 1/f noise in Graphene (Elisabetta Paladino, Francesco Pellegrino & Giuseppe Angilella)
- **Eccitazioni topologiche** (cf Science Colloquium Renato Pucci next November?)
  characterization, sensing, quantum-to-classical, error correction, dynamical decoupling, reservoir engineering, quantum control
- **Ultrastrong light-matter coupling** (with Elisabetta Paladino)
- **Quantum Deep Learning and noise** (still alone!)
- **Atomtronics** mesoscopic physics with atoms (L. Amico)

overview of quantum technologies goals

- **Demonstrating "quantum supremacy"**, i.e. that task actually exist where quantum exponentially outperforms classical, would be a milestone for fundamental science.
  - Develop applications with immediate socio-economic impact
  - Spin-off of the research already has and will have technological impact

- To this end the **EU Flagship on QUTEes** aims to



- Create a favourable **ecosystem of innovation and business creation** for QUTEes
- Facilitate a **new level of coordination between academia and industry** to move advances in quantum technologies from the laboratory to industry.
- Create a **new generation of quantum technology professionals** in Europe through focused education at the **intersection of science, engineering and business**, and by strengthening public awareness of key ideas and capabilities.
- Coordinate public investments/strategies in quantum technologies at the European level.
- Promote the **involvement of member regions that do not currently have a strong quantum technologies research programme.**

Grazie per l'attenzione!

"Quantum Parrot"
David Crooks

e per il supporto non solo morale

Università di Catania
Dipartimento di Fisica e Astronomia

IMM
Istituto per la Microelettronica e Microsistemi

INFN *Istituto Nazionale di Fisica Nucleare*

Centro Siciliano di Fisica Nucleare e Struttura della Materia