# Quantum Mechanics: foundations and applications

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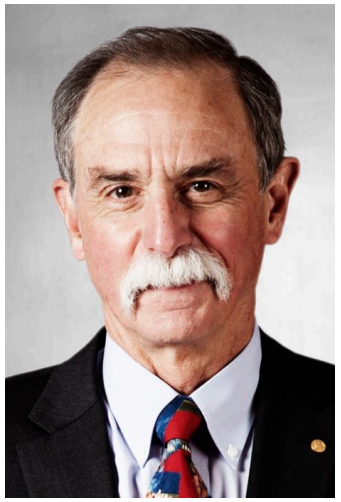
# Physics Nobel Prizes in Quantum Mechanics

2012

*for ground-breaking experimental methods that enable measuring and manipulation of **individual quantum systems***

2022



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

# Building blocks of Quantum Mechanics

## Qubit

*for ground-breaking experimental methods that enable measuring and manipulation of **individual quantum systems***

## Entanglement

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

# From Foundations to Applications

**Conceptual foundations (1920-40)**

**The meaning of the theory:** Bohr-Einstein debate on the role of the wave function.

**1935 is a golden year**: EPR paper and Schrödinger's cat paper.
**Entanglement** enters the discussion.

# From Foundations to Applications

**Conceptual foundations (1920-40)** → **Mathematics & theory (1950-)**

**Mathematics:** Setting the mathematical basis of the theory: Kraus (1969-70), Lindblad (1976), Gorini-Kossakowski-Sudarshan (1976)

**Theory:** Hidden variables – Bohm (1952); **nonlocality – Bell** (1964)

$$\langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle \leq 2$$

# From Foundations to Applications

**Conceptual foundations (1920-40)** → **Mathematics & theory (1950-)** → **Quantum Information (1980-)**

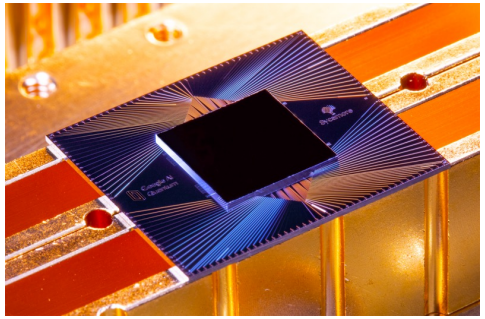
**Theory**: How information can be encoded, manipulated, transmitted and exploited according to quantum principles: cryptography and computation. **Qubit** (1995)

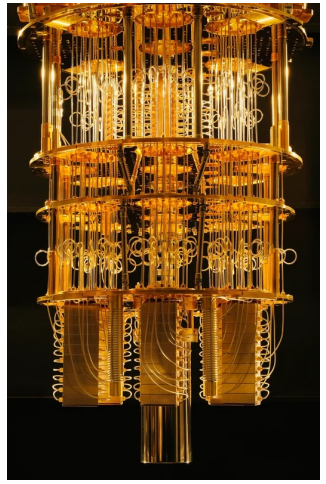
**Experiments:** Quantum optics, trapped ions, cold atoms, optomechanics, superconducting qubits, …

# From Foundations to Applications

**Conceptual foundations (1920-40)** → **Mathematics & theory (1950-)** → **Quantum Information (1980-)** → **Quantum Technologies (2000-)**

Quantum **computers,** quantum **simulators,** quantum **sensors,** quantum **communication,** quantum **metrology**, …



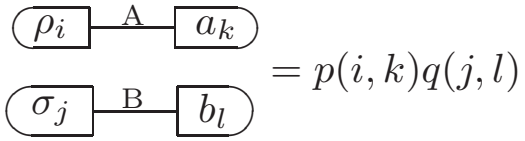


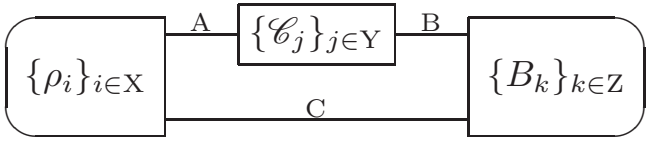
# Quantum Mechanics in Italy: milestones

**D'Ariano:** Quantum Information & foundations.

**Quantum theory as an information theory (it from qubit).**

G. Chiribella, G.M. D'Ariano, P. Perinotti, "Informational derivation of quantum theory", Physical Review A 84, 012311 (2011)

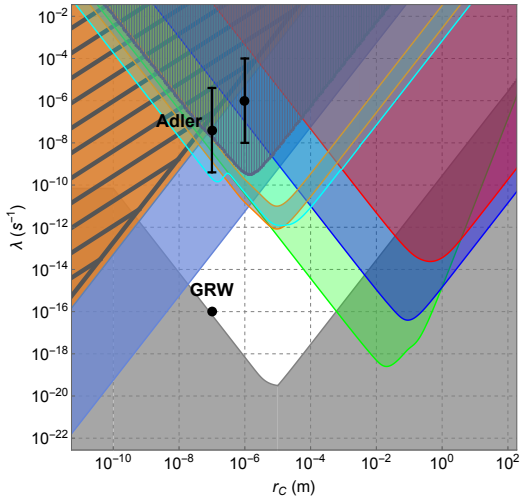



# Quantum Mechanics in Italy: milestones

**Ghirardi, Rimini, Weber:** Quantum foundations. **Models of spontaneous wave function collapse**.

G.C. Ghirardi, A. Rimini, T. Weber, "Unified dynamics for microscopic and macroscopic systems" Physical review D 34, 470 (1986)

$$\frac{\mathrm{d}\hat{\rho}_t}{\mathrm{d}t} = -\frac{i}{\hbar}\left[\hat{H},\hat{\rho}_t\right] - \frac{\lambda}{2m_0^2}\int \mathrm{d}\mathbf{x}\int \mathrm{d}\mathbf{y}\, g(\mathbf{x}-\mathbf{y})\left[\hat{M}(\mathbf{x}),\left[\hat{M}(\mathbf{y}),\hat{\rho}_t\right]\right]$$

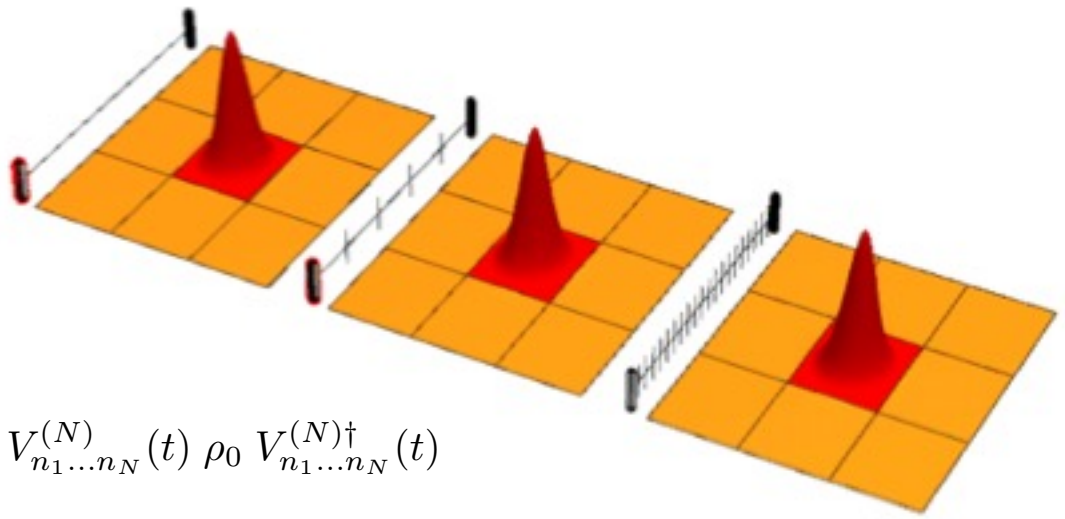


# Quantum Mechanics in Italy: milestones

**Pascazio:** Quantum Foundations, information.

**Quantum Zeno effect → role of measurement**

S. Pascazi, M. Namiki, "Dynamical quantum Zeno effect", Physical Review A 50, 4582 (1994). P. Facchi, S. Pascazio, "Quantum Zeno subspaces", Physical Review Letters 89, 080401 (2002)



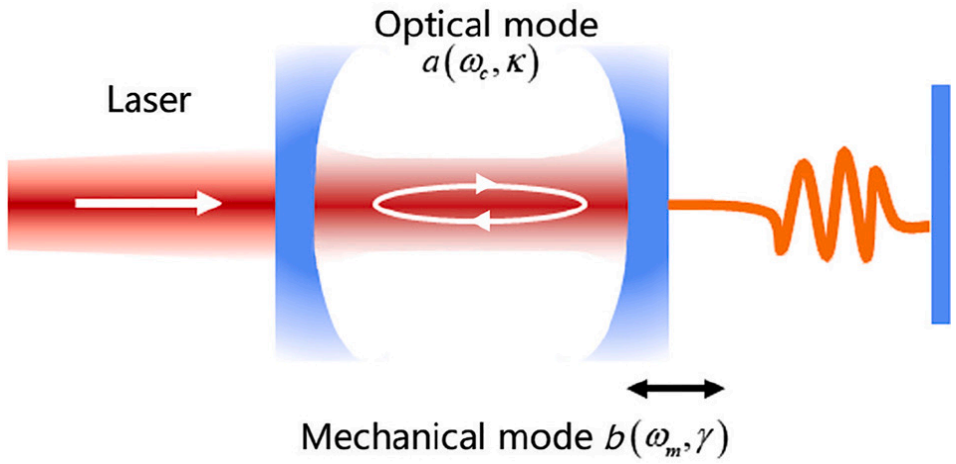
$$\rho(t) = \hat{V}_t^{(N)} \rho_0 = \sum_{n_1,\ldots,n_N} V^{(N)}_{n_1 \ldots n_N}(t)\ \rho_0\ V^{(N)\dagger}_{n_1 \ldots n_N}(t)$$

$$V^{(N)}_{n_1 \ldots n_N}(t) = P_{n_N} U\left(t/N\right) P_{n_{N-1}} \cdots P_{n_2} U\left(t/N\right) P_{n_1}$$

# Quantum Mechanics in Italy: milestones

**Mancini & Tombesi:** Theoretical development of **optomechanics**

S. Mancini, P. Tombesi "Quantum noise reduction by radiation pressure", Physical Review A 49, 4055 (1994).

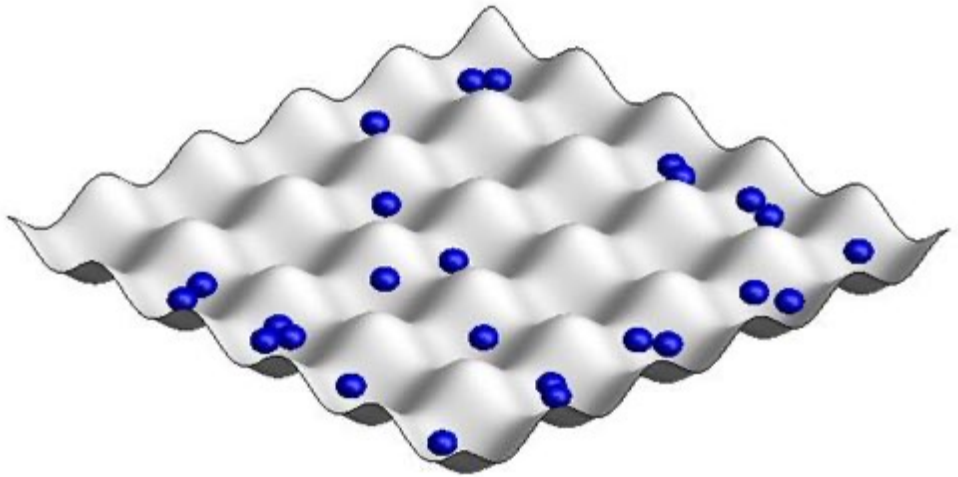



$$H_{tot} = -\hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b - \hbar g_0 a^\dagger a \frac{x}{x_{zpf}} + i\hbar E\left(a - a^\dagger\right)$$

# Quantum Mechanics in Italy: milestones

## **S. Stringari:** Theory of **cold atom physics**

F. Dalfovo, S. Giorgini, L.P. Pitaevskii, S. Stringari, "Theory of Bose-Einstein condensation in trapped gases", Reviews of Modern Physics 71, 463 (1999)

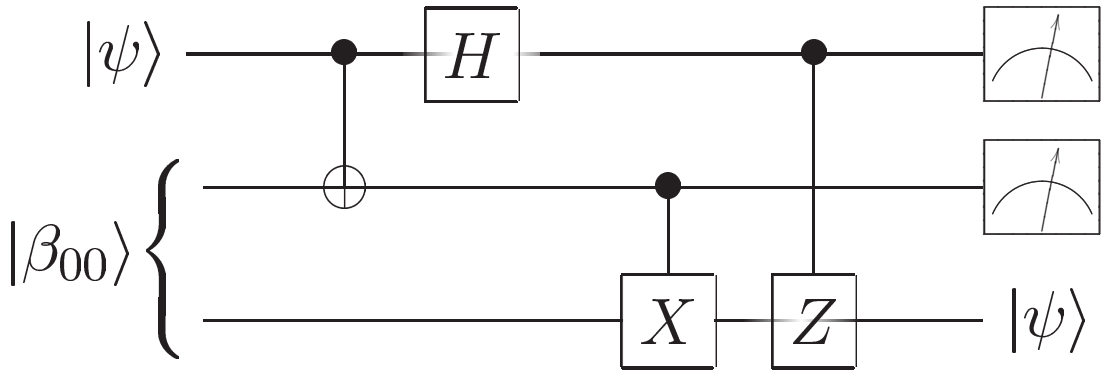


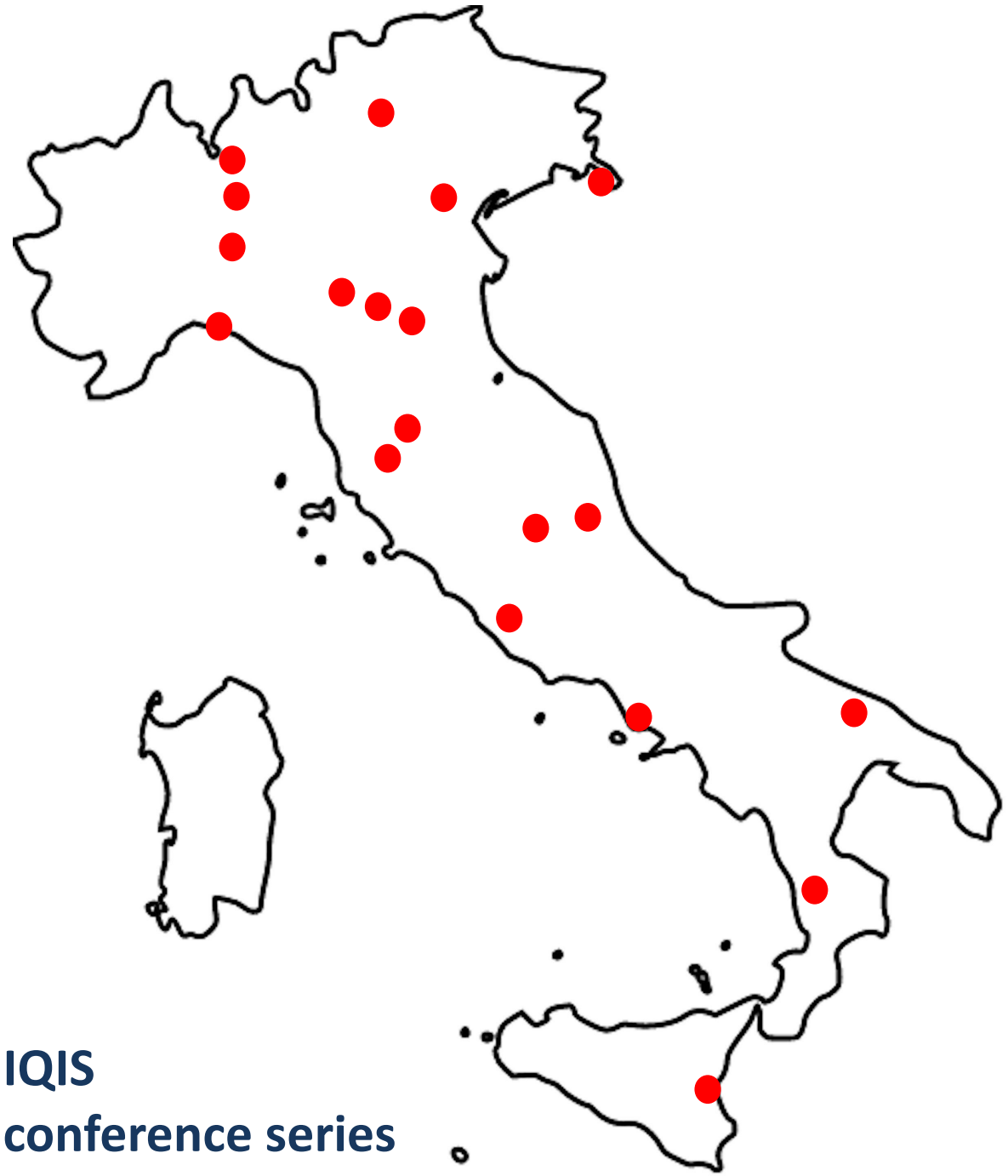
$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2}+V(\mathbf{r})+\frac{4\pi\hbar^2 a_s}{m}|\psi(\mathbf{r})|^2\right)\psi(\mathbf{r})=\mu\psi(\mathbf{r})$$

# Quantum Mechanics in Italy: milestones

**De Martini:** Experimental quantum optics. First realization of **quantum teleportation** (independently of Zeilinger)

D. Boschi, S. Branca, F. De Martini, L. Hardy, S. Popescu, "Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels", Physical Review Letters 80, 1121 (1998)



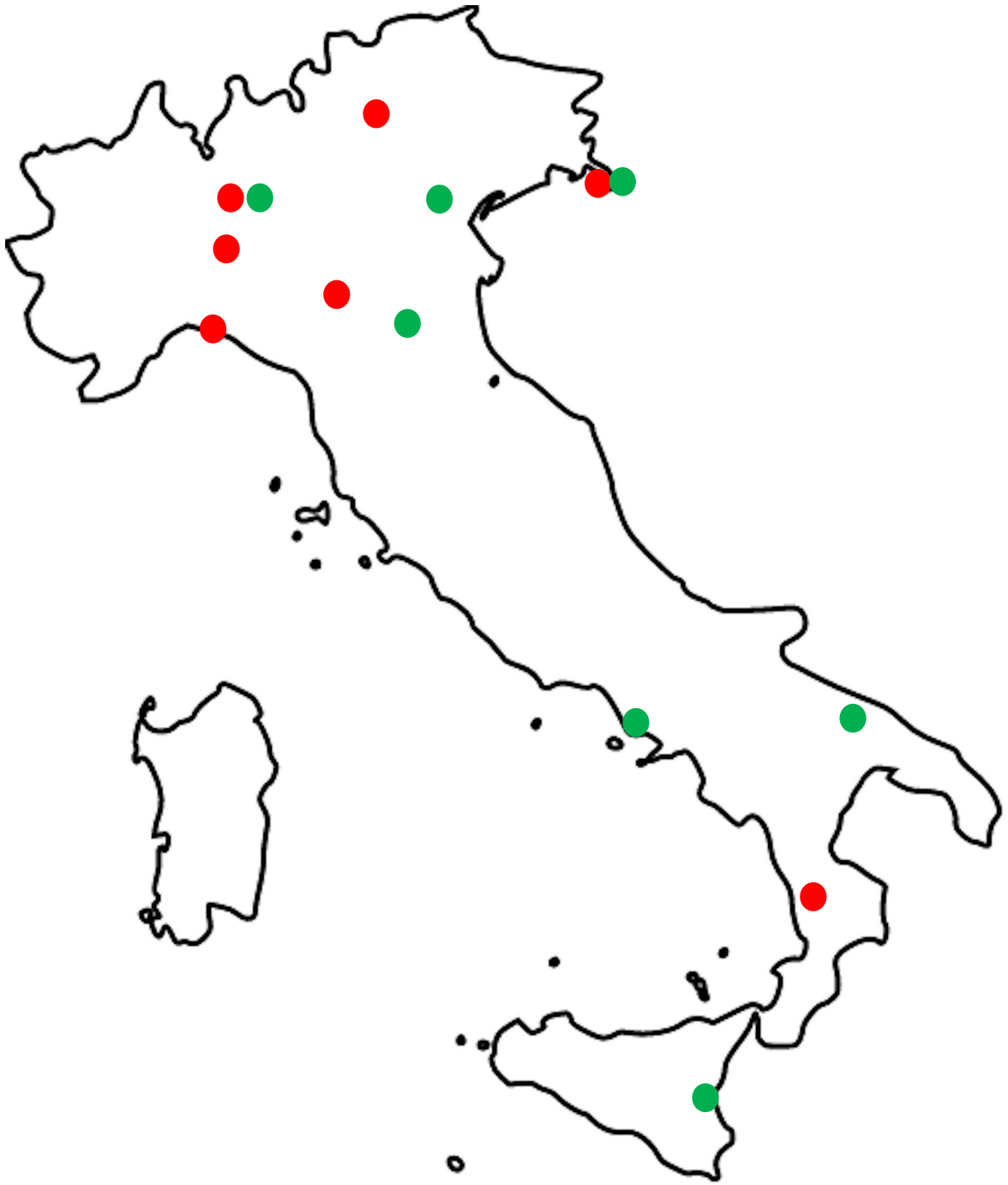
**IQIS**
**conference series**

# Quantum Mechanics at INFN today

Research in all major sectors:

- Quantum Foundations: theory, math & experiments
- Quantum Information: theory
- Quantum Information: many relevant experimental platforms
- QuTech: communication, sensing, simulations, recently also computing

**Italian community: very active, diversified and leader of important international research projects**



# Quantum theoretical Initiatives within INFN

**BELL**

Foundations of quantum mechanics: Trieste, Genova, Milano, Pavia, Parma, Cosenza, Trento

**QUANTUM**

Quantum Information: Bari, Bologna, Catania, Milano, Napoli, Padova, Trieste

# INFN and Quantum Technologies

- Founding member of the PNRR National Center on **HPC and Quantum Computing → EuroQCS**
- Founding member of the PNRR **National Quantum Science and Technology Institute**
- Member of CERN's hub in the **IBM Quantum Network**
- Partner of the FERMILAB project **SQMS**
- **Uncountable international collaborations and joint projects**

# Future challenges

**Fundamental research in Quantum Mechanics:** INFN has long-standing ties with research in Quantum Mechanics (more theory than experiments), and supported several internationally renown groups. These ties should be strengthened.

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# Thank you