UNIVERSITÀ DEGLI STUDI DI MILANO
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QUANTUM SYSTEMS INTERACTING WITH COMPLEX ENVIRONMENTS

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WHAT THIS TALK IS ABOUT

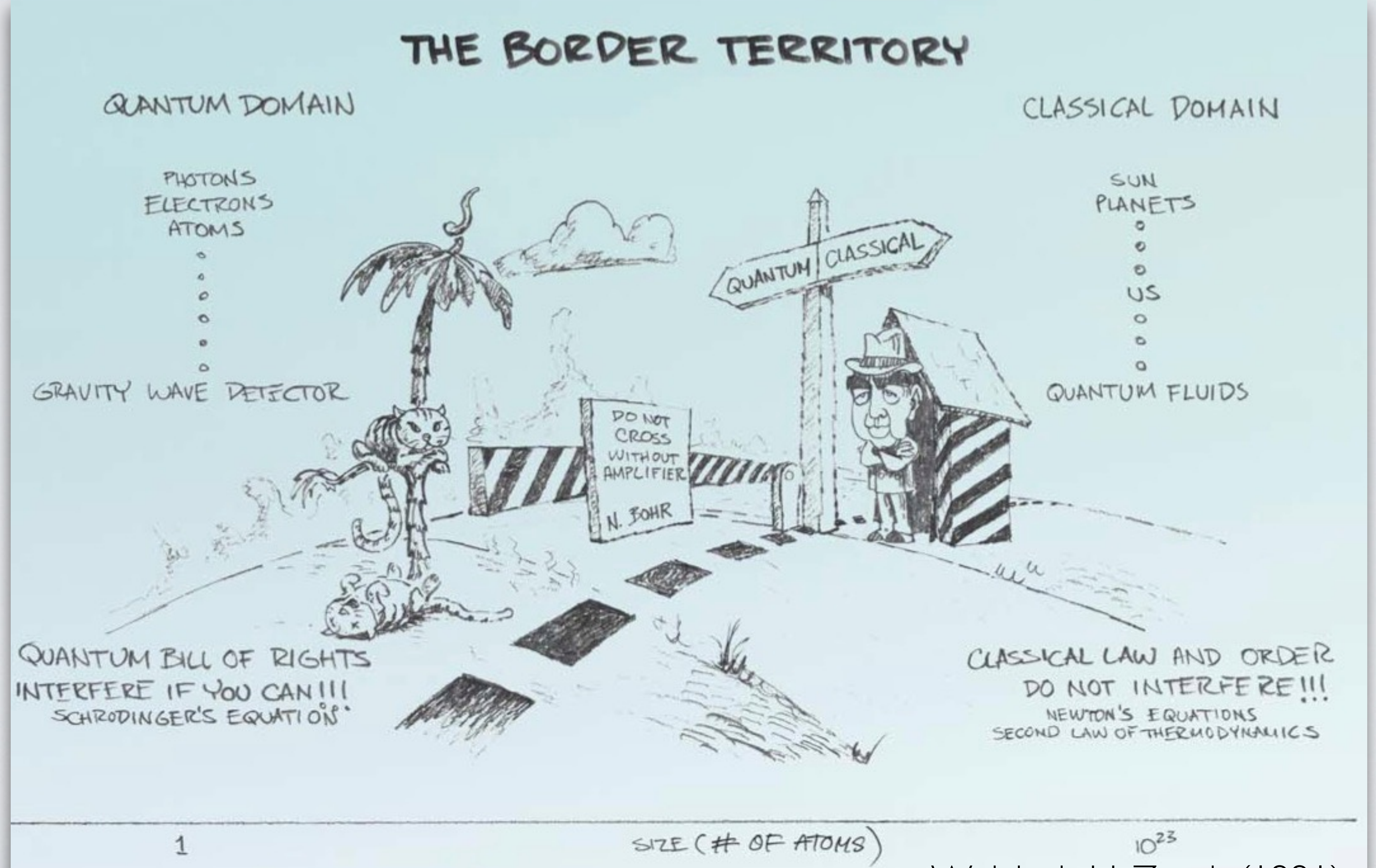
- A way to describe the interaction between a quantum system and its (complex) environment
- How quantum systems may be used to probe the environment

$$i\hbar\frac{\partial}{\partial t}\left|\psi\right\rangle = H(t)\left|\psi\right\rangle$$

INTERACTION WITH THE ENVIRONMENT

- There is no such thing as an isolated system
- Quantum systems, being microscopic, are particularly sensitive to perturbations
- The interaction with the environment generally induces **decoherence**: a decay of quantum correlations

QUANTUM-TO-CLASSICAL TRANSITION



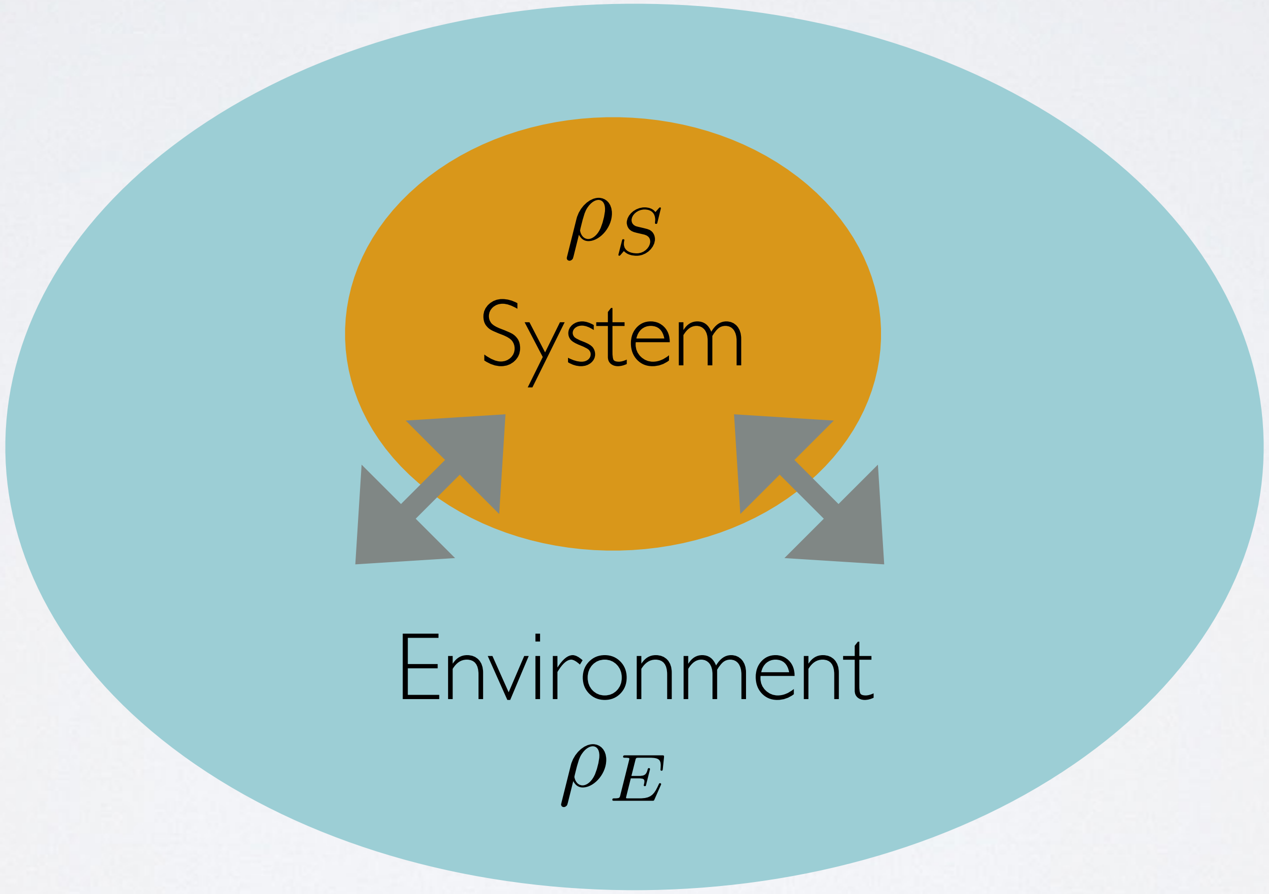
Wojciech H. Zurek (1991)

QUANTUM TECHNOLOGIES

- Quantum systems can be employed for a variety of tasks
  - computation and manipulation of information
  - cryptography
  - simulation of other quantum systems
- Quantum properties (**entanglement**) are a resource for greater efficiency of quantum technologies with respect to classical ones

DYNAMICS OF OPEN QUANTUM SYSTEMS

Density matrix: $\rho = \sum_i p_i \left|\psi_i\right\rangle \left\langle\psi_i\right|$



$$\rho_S(t) = \mathrm{Tr}_E[U(t)(\rho_S(0) \otimes \rho_E(0))U^\dagger(t)]$$

QUANTUM SYSTEMS INTERACTING WITH CLASSICAL ENVIRONMENTS

- Complex systems with many degrees of freedom must be studied with approximate methods
- Certain environments can be accurately described in terms of classical stochastic processes
- Classical noise is found experimentally in many devices (superconducting, solid state…)

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

E. Paladino, Y. M. Galperin, G. Falci, and B. L. Altshuler
Rev. Mod. Phys. **86**, 361 – Published 3 April 2014

nature COMMUNICATIONS

ARTICLE

Received 23 Sep 2013 | Accepted 31 Oct 2013 | Published 29 Nov 2013 DOI: 10.1038/ncomms3851 OPEN

Experimental recovery of quantum correlations in absence of system-environment back-action

Jin-Shi Xu[1], Kai Sun[1], Chuan-Feng Li[1], Xiao-Ye Xu[1], Guang-Can Guo[1], Erika Andersson[2], Rosario Lo Franco[3] & Giuseppe Compagno[3]

ARTICLE

Received 13 Aug 2012 | Accepted 11 Dec 2012 | Published 29 Jan 2013 DOI: 10.1038/ncomms2383

Motional averaging in a superconducting qubit

Jian Li[1], M.P. Silveri[2], K.S. Kumar[1], J.-M. Pirkkalainen[1], A. Vepsäläinen[1], W.C. Chien[1], J. Tuorila[2], M.A. Sillanpää[1,3], P.J. Hakonen[1], E.V. Thuneberg[2] & G.S. Paraoanu[1]

nature physics

PUBLISHED ONLINE: 8 MAY 2011 | DOI: 10.1038/NPHYS1994

Noise spectroscopy through dynamical decoupling with a superconducting flux qubit

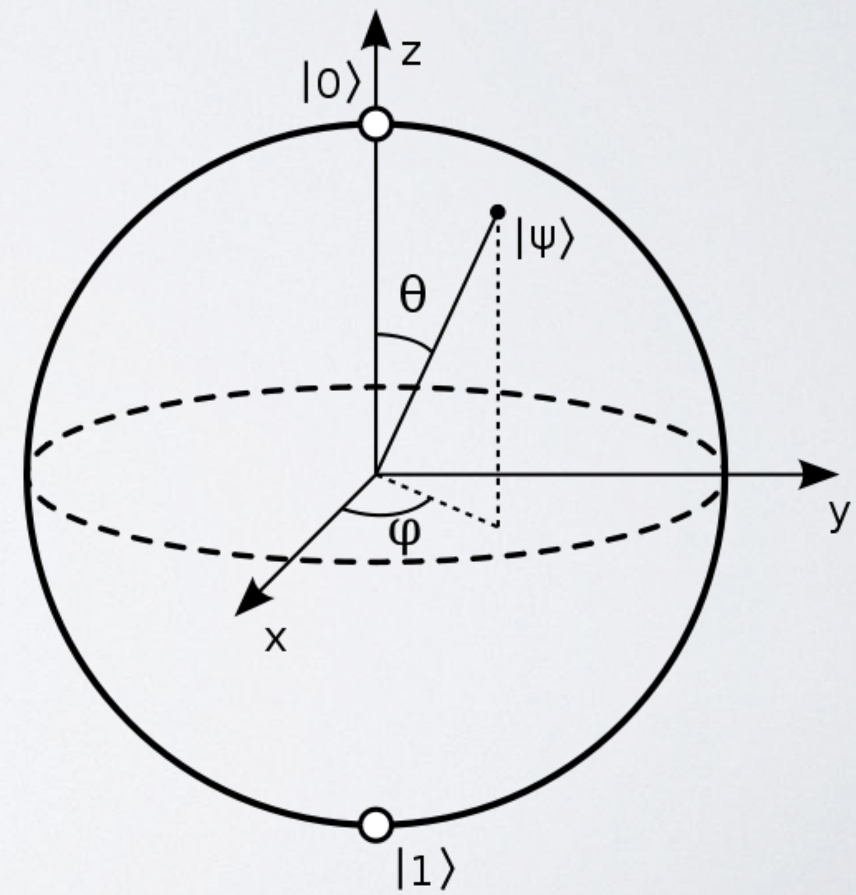
Jonas Bylander[1]*, Simon Gustavsson[1], Fei Yan[2], Fumiki Yoshihara[3], Khalil Harrabi[3†], George Fitch[4], David G. Cory[2,5,6], Yasunobu Nakamura[3,7], Jaw-Shen Tsai[3,7] and William D. Oliver[1,4]

THE QUBIT

- The **qubit** is the simplest quantum system: two energy levels

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

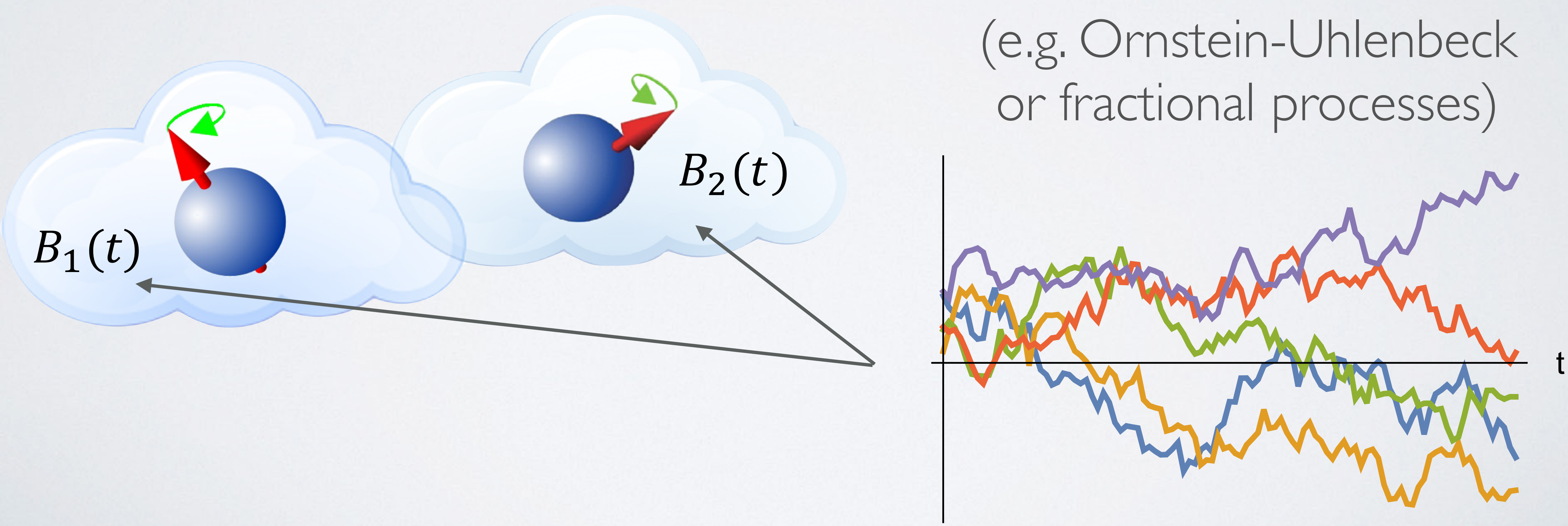
- Many systems can be considered as qubits
  - Nuclear or electronic spin
  - The polarisation of photons
  - Two energy levels of an ion
  - Superconducting devices



DYNAMICS OF QUBITS IN CLASSICAL ENVIRONMENTS

Qubits interacting with noisy environments described by classical stochastic processes

Gaussian noise
(e.g. Ornstein-Uhlenbeck
or fractional processes)



DYNAMICS OF QUBITS IN CLASSICAL ENVIRONMENTS

$$\mathcal{H}[B(t)]$$

Solve the Schrödinger equation

$$U(t) = \mathcal{T} \exp\left[-i \int_{t_0}^{t} \mathcal{H}(t')dt'\right]$$

Average over all possible realisations of the stochastic process:

$$\rho(t) = \langle U(t)\rho_0 U^\dagger(t)\rangle_{B(t)}$$

DYNAMICS OF QUBITS IN CLASSICAL ENVIRONMENTS

$$\mathcal{H} = \hbar\omega\sigma_z + \mathcal{H}_I(t)$$

Longitudinal noise
(dephasing)

$$\mathcal{H}_i = \lambda B(t)\sigma_z$$

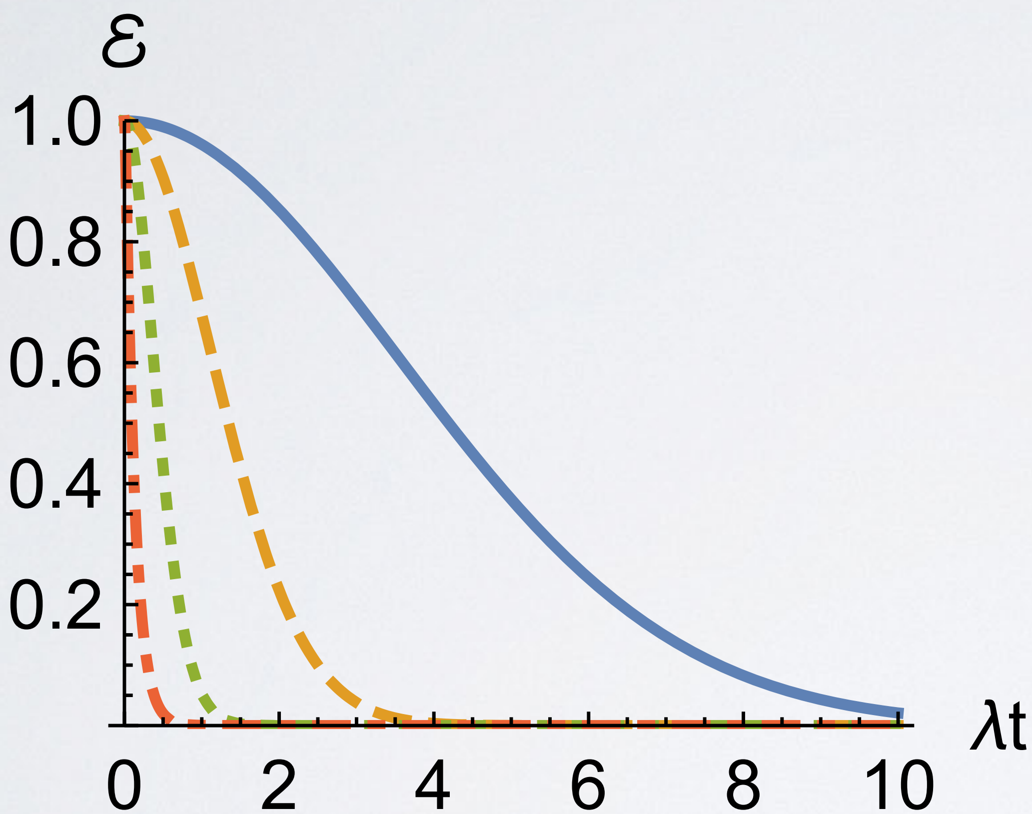
Out-of-resonance
spectrum

Transverse noise
(hopping/damping)

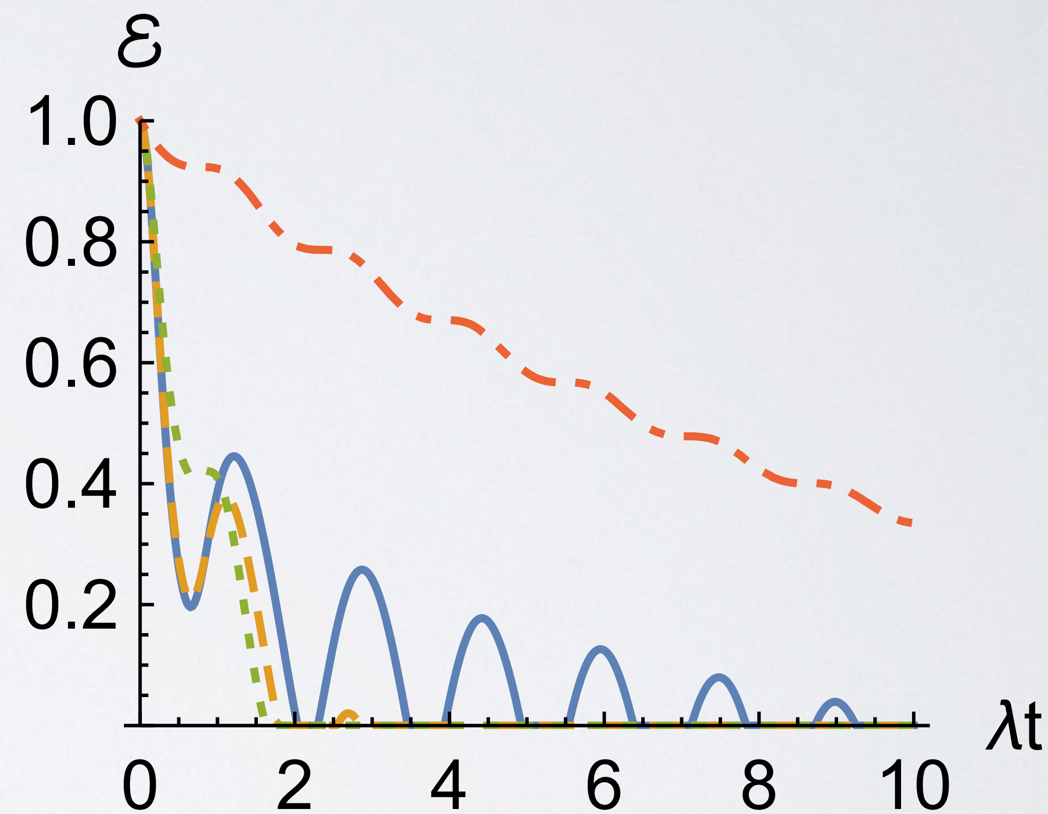
$$\mathcal{H}_i = \lambda B(t)\sigma_x$$

Resonant
spectrum

DYNAMICS OF QUBITS IN CLASSICAL ENVIRONMENTS



Dephasing noise



Transverse noise

MR, C Benedetti, and MGA Paris, Int. J. Quantum Inform. **12**, 1560003 (2014)
MR, MGA Paris, in preparation

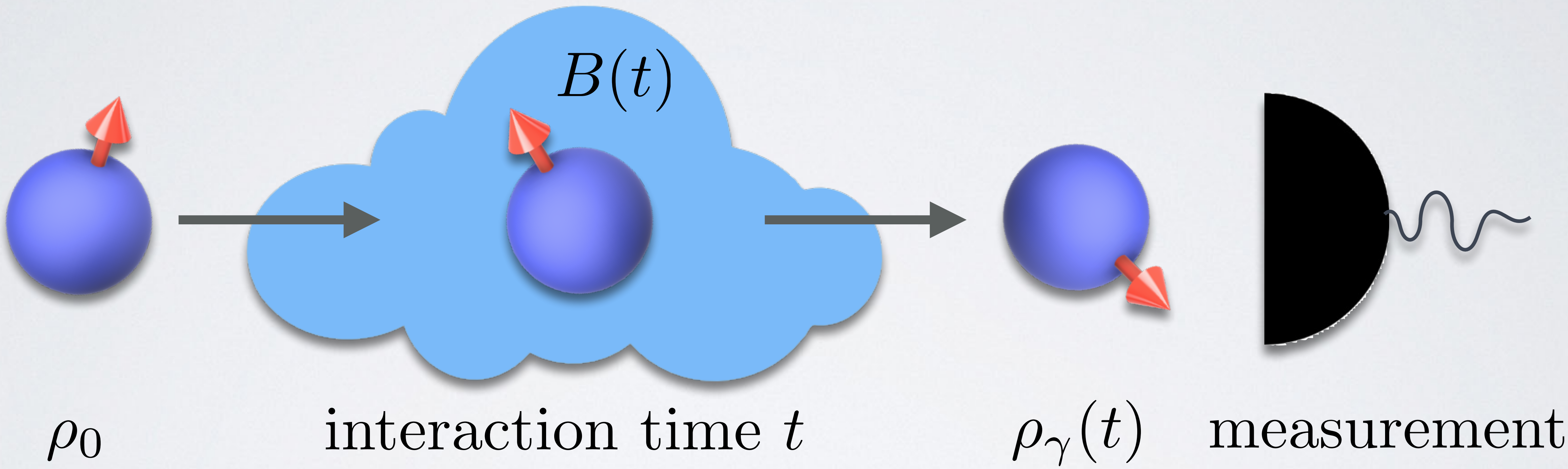
QUANTUM PROBES

Quantum **Pro**bes for
Complex **S**ystems

Use quantum systems as **probes** for estimating parameters of complex environments:

- Less intrusive
- Quantum correlations may allow for better precision

QUANTUM PROBES



QUANTUM PROBES

- Estimate the spectral width γ of classical Gaussian noise described by a Lorentzian spectrum

$$S(\omega) = \frac{\gamma^2}{\gamma^2 + \omega^2}$$

- Evaluate the best precision achievable

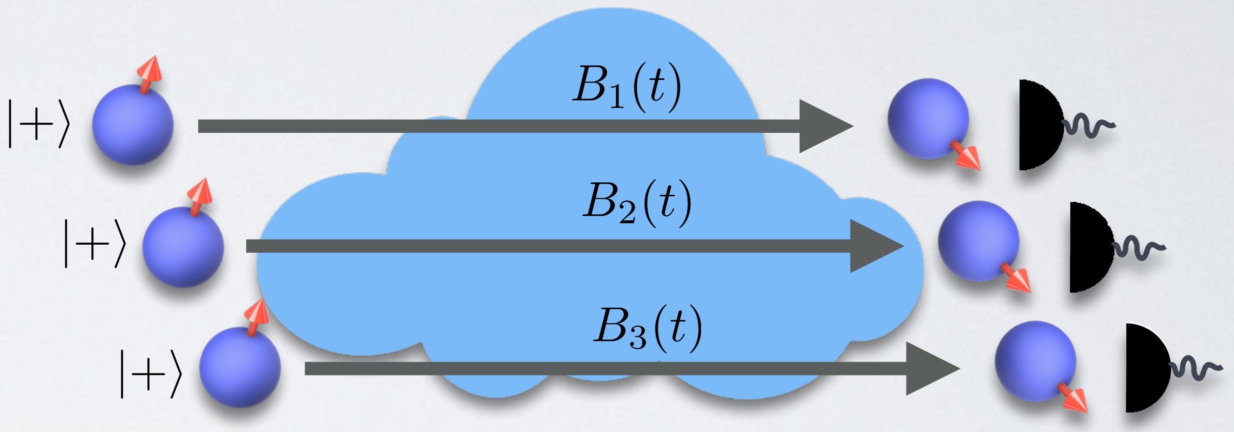
$$\delta\gamma \geq \frac{1}{\sqrt{MH(\gamma)}}$$

- $H(\gamma)$ is the **quantum Fisher information**

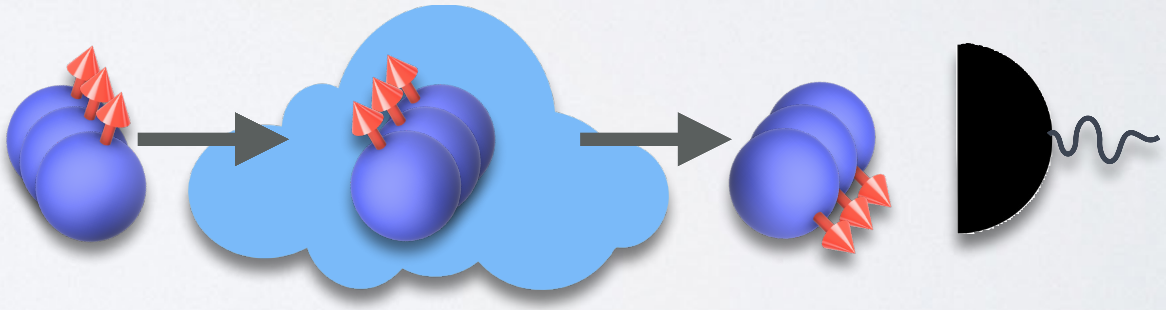
MR and MGA Paris, *Phys. Rev. A* **92**, 010302(R) (2015)

QUANTUM PROBES

The probes are made of N qubits.



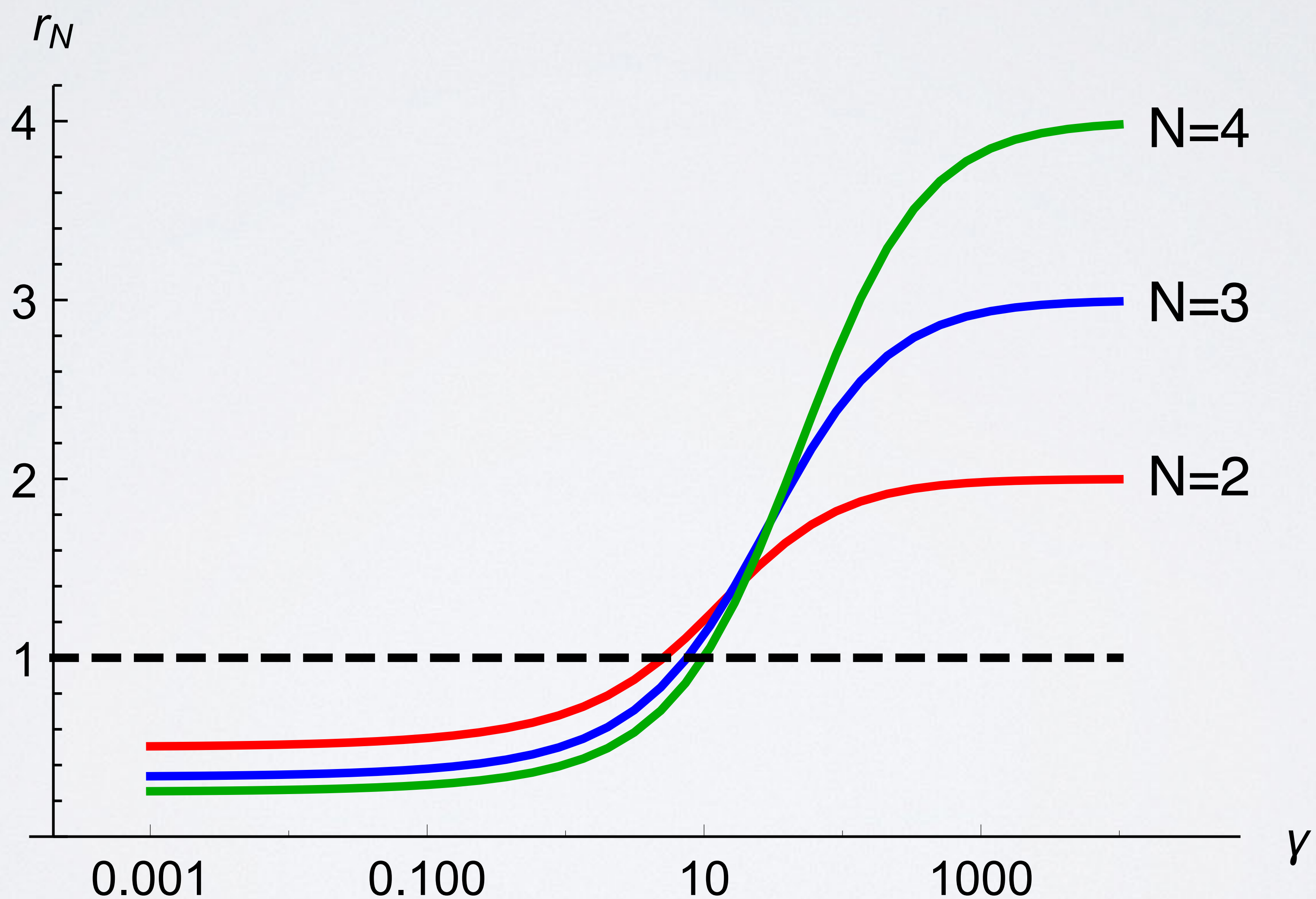
We compare the best precision achievable when the qubits are entangled and when they are not



MR and MGA Paris, *Phys. Rev. A* **92**, 010302(R) (2015)

QUANTUM PROBES

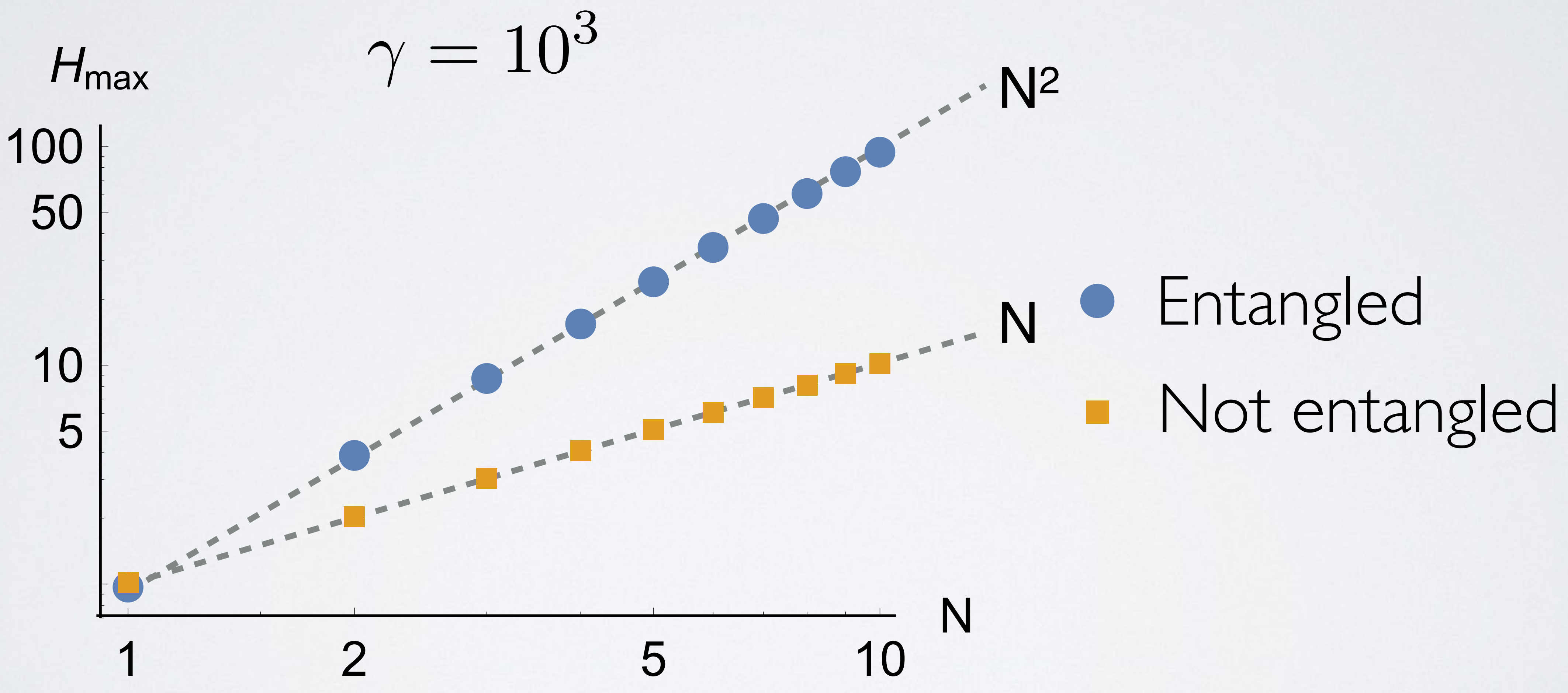
- In a certain region of γ, entangled qubits allow for better estimation



MR and MGA Paris, *Phys. Rev. A* **92**, 010302(R) (2015)

QUANTUM PROBES

Quantum correlations can be a resource for probing complex environments!



MR and MGA Paris, *Phys. Rev. A* **92**, 010302(R) (2015)

SUMMARY

- The environment can be described **classically** in many situations
- Classical environments can also induce **revivals of quantum correlations**
- Quantum systems can be used as **probes** for complex environments and **quantum correlations** can be a resource for this task