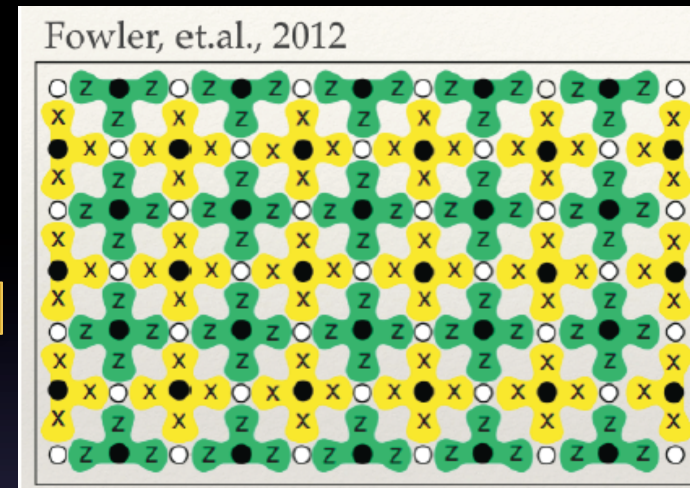
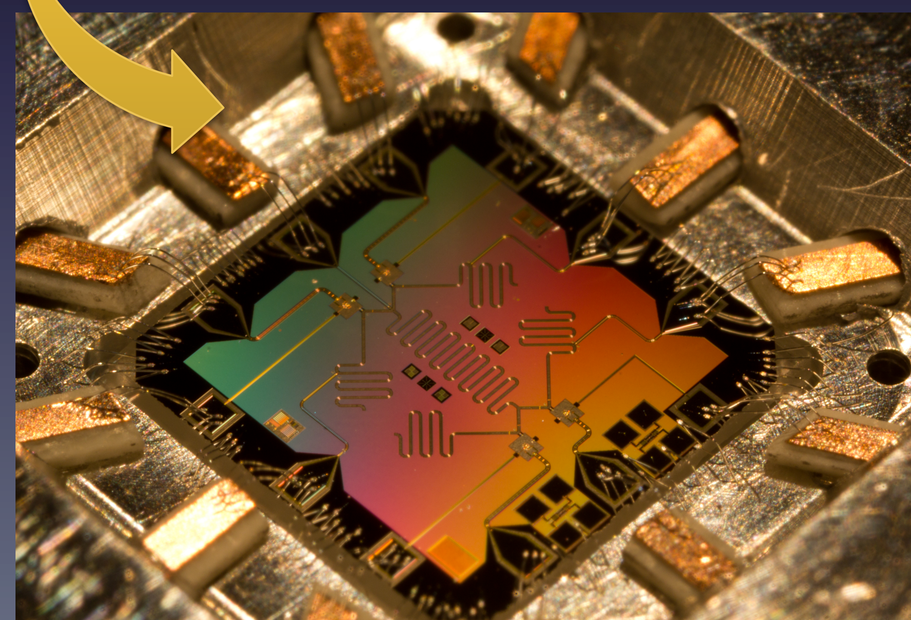

Quies
PROTECTION AUDITIVE
GEHOORBESCHERMING
Cire naturelle - Natuurlijke was
Confort longue durée
Langdurig comfort
27dB
12 Paires - Paar


Fowler, et.al., 2012


a place for everything
with everything in its place!



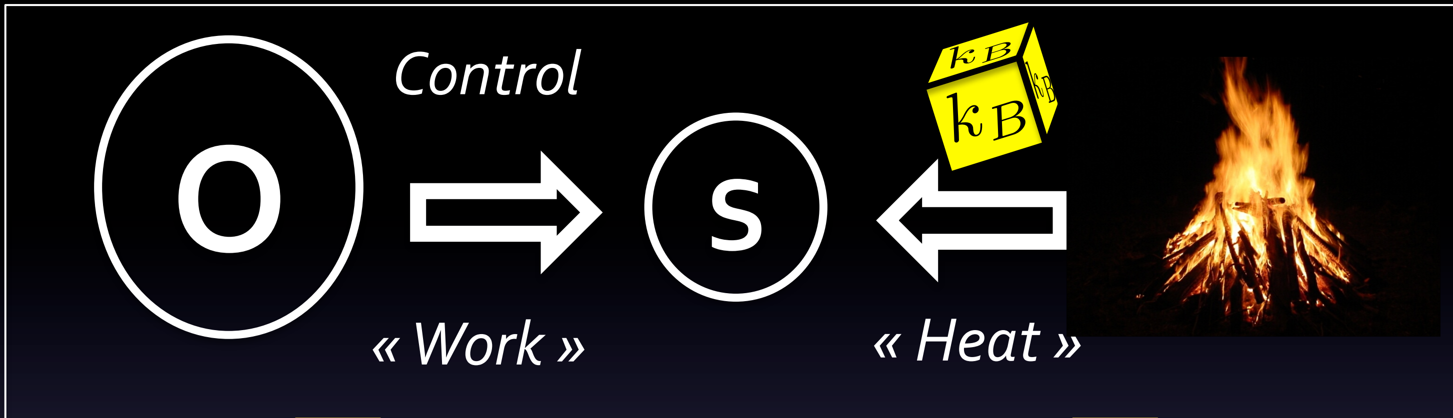
Energetic footprints of quantum noise

Alexia Auffèves

CNRS & Université Grenoble-Alpes

Quantum Thermodynamics conference, KITP, June 25-29, 2018

Thermodynamics and noise

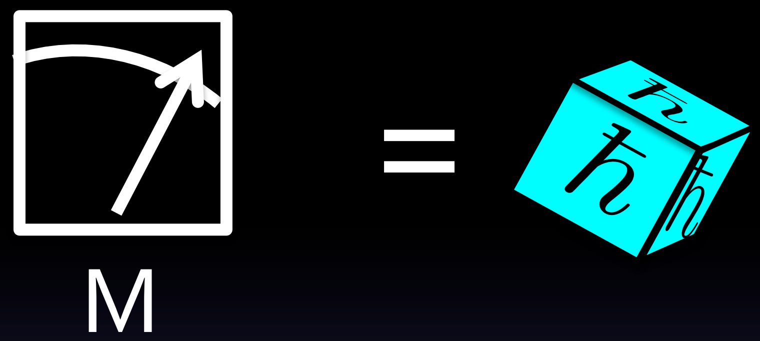


Work extraction from **thermal** noise
=> Heat engines

Thermal noise =>
Irreversibility &
Fundamental bounds

- **Thermodynamics = Theory of control against noise**
- **Thermodynamics is based on randomness**

Measurement induced quantum noise

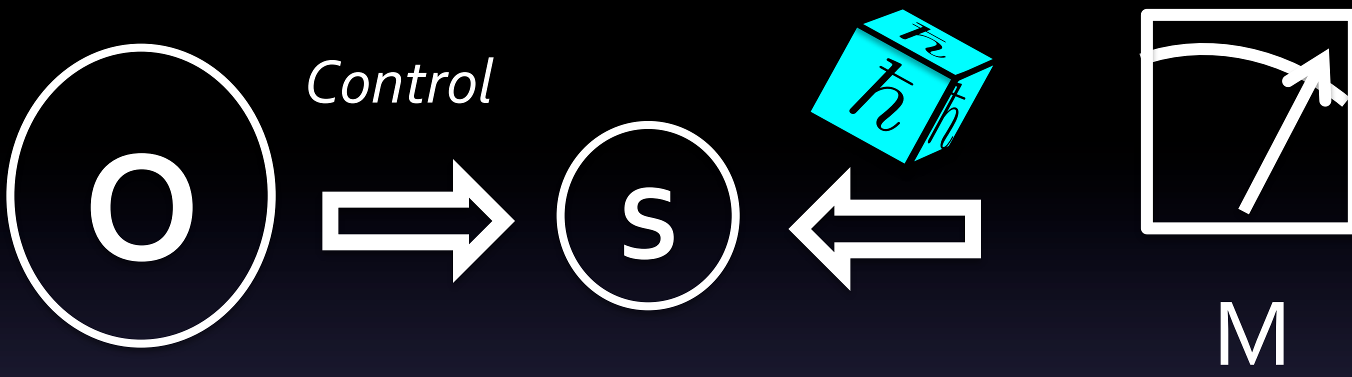


Quantum measurement backaction =>
Genuine **quantum randomness** and **quantum noise**

Quantum time arrow, quantum heat

- Forget about temperature!
- **Rebuild thermodynamics on quantum measurement**

Quantum measurement based thermodynamics



Work extraction from **quantum** fluctuations?

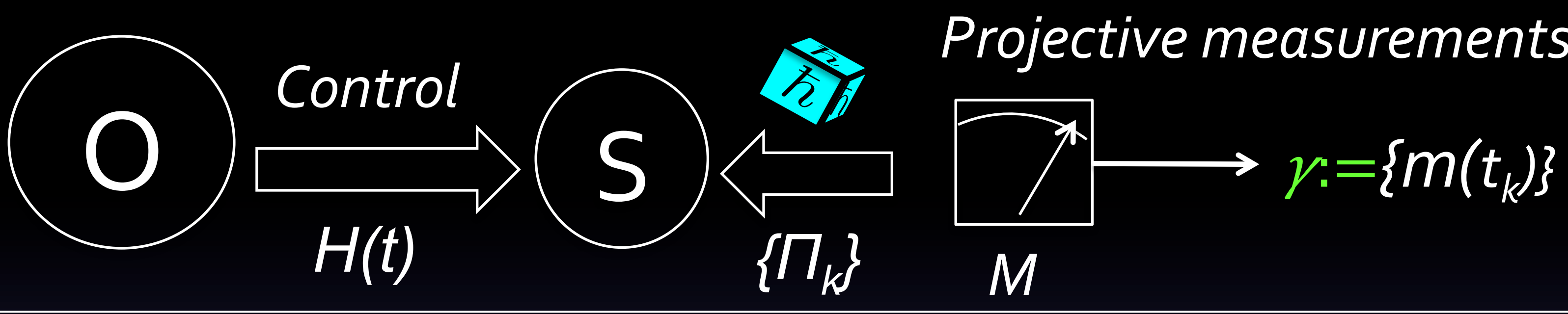
Quantum fundamental bounds?

Energetic and entropic footprints of **quantum** control?

Outline

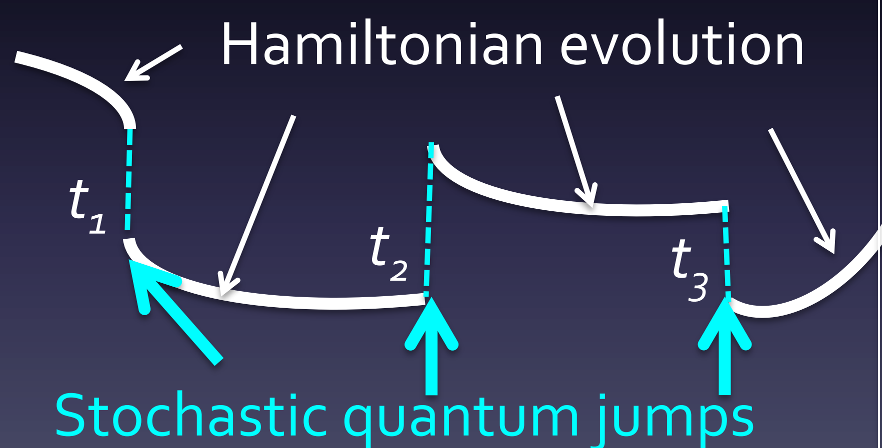
- **Introduction: Rebuilding quantum thermodynamics on quantum measurement**
- A measurement-powered quantum engine
- Work cost of quantum control
- Conclusion - Outlook

Scenery and definitions



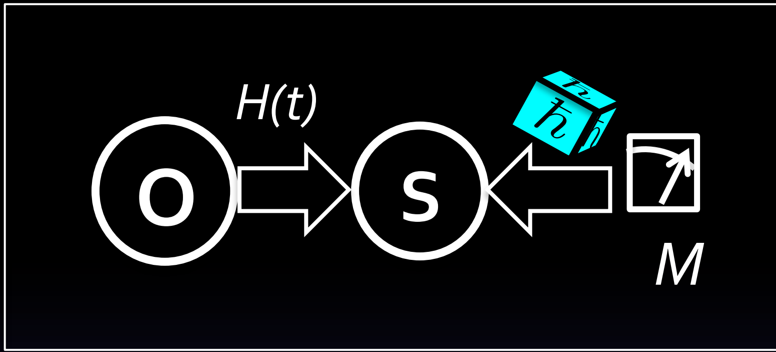
- Pure initial state $|\psi(t_o)\rangle$
- Read measurement outcomes:

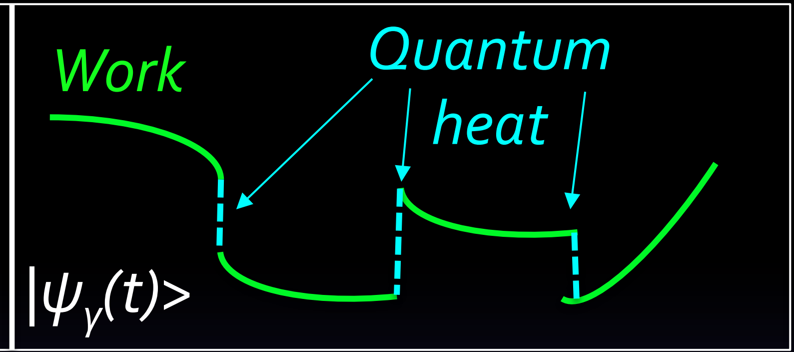
Stochastic quantum trajectory $|\psi_\gamma(t)\rangle$



- Unread measurement outcomes :
- $|\psi(t_o)\rangle\langle\psi(t_o)| \rightarrow \rho(t) = \Sigma\gamma\, P[\gamma]\, |\psi_\gamma(t)\rangle\langle\psi_\gamma(t)|$

First Law





Read measurement outcomes

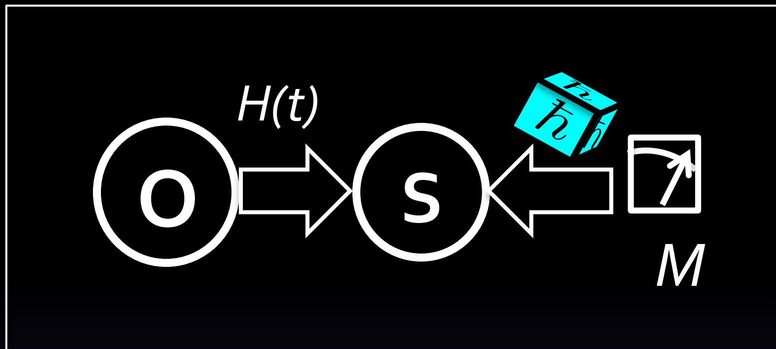
- Internal energy: $U_\gamma(t) := \langle\psi_\gamma(t)|H(t)|\psi_\gamma(t)\rangle$
- Work: $W[\gamma](t_k \to t_{k+1}) := U_\gamma(t^-_{k+1}) - U_\gamma(t^+_k)$
- Quantum heat: $Q_q[\gamma](t_k) := U_\gamma(t^+_k) - U_\gamma(t^-_k)$
- $\Delta U_\gamma = W[\gamma] + Q_q[\gamma]$

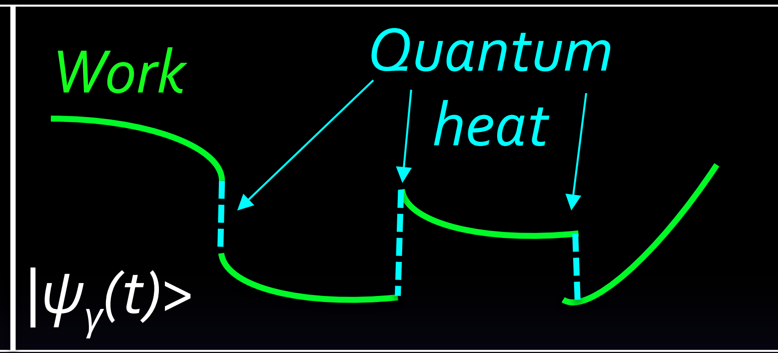
Unread measurement outcomes

- Work : Energy transfers during unitaries
- Quantum heat: Energy transfers during non-unitaries

Elouard et al, npj QI 3:9 (2017)

Second Law





Stochastic entropy production

- $\Delta_i S[\gamma]$:=log($P_F[\gamma]/P_B[\gamma_r]$) with γ:={$m(t_k)$}; γr:={$m(t_{N-k})$}
  - ➢ $P_F[\gamma] = p_o(m(t_o))\, |< m(t_{k+1})|G|\, m(t_k)>|^2$
  - ➢ $P_B[\gamma_r] = p_N(m(t_N))\, |< m(t_{k+1})|G^+|\, m(t_k)>|^2$
  - ➢ G: propagator

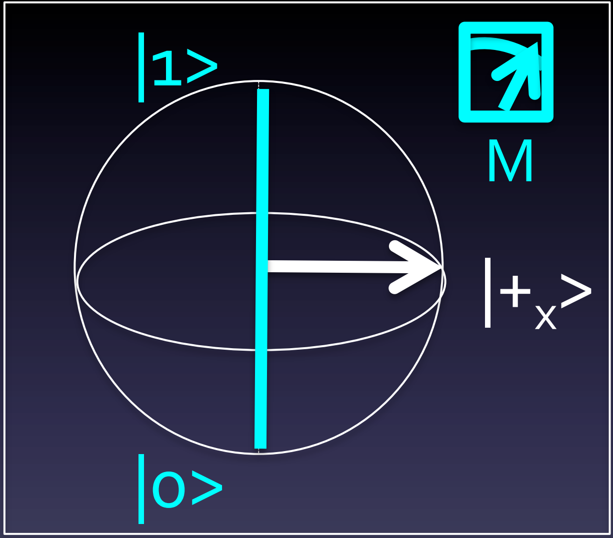
=> $\Delta_i S[\gamma] = -\log(p_N(m(t_N)) + \log(p_o(m(t_o))$

Mean entropy production

- $<\Delta_i S[\gamma]> = \Delta S_{VN}$ with $S_{VN} = -\mathrm{Tr}[\rho \log \rho]$ Von Neumann entropy

Meet the quantum heat

System: a Qubit, $H=[h\nu_0/2]\ \sigma_{Z,}$
Transformation: (i) Preparation in $|+_x>$ (ii) Measurement of $M=\sigma_z$



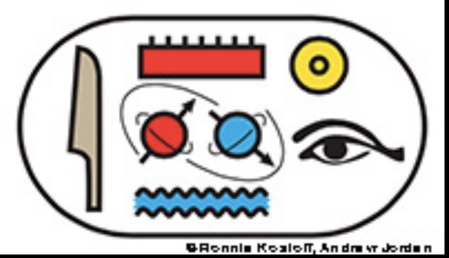
2 stochastic trajectories:

- $\Gamma_1 = [|+_x>, |0>]$
- $\Gamma_2 = [|+_x>, |1>]$

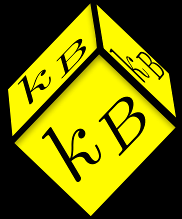
Energetic balance

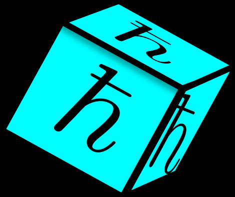
- Initial energy $U_i = 0$
- Final energy $U_f = +/- h\nu_0/2$
- $\Delta U[\gamma] = +/- h\nu_0/2 = Q_q[\gamma]$

- **Energetic footprint of quantum noise: Quantum heat**
- **A purely quantum term due to measurement back-action**



Outline





- Introduction: Rebuilding quantum thermodynamics on quantum measurement and quantum noise
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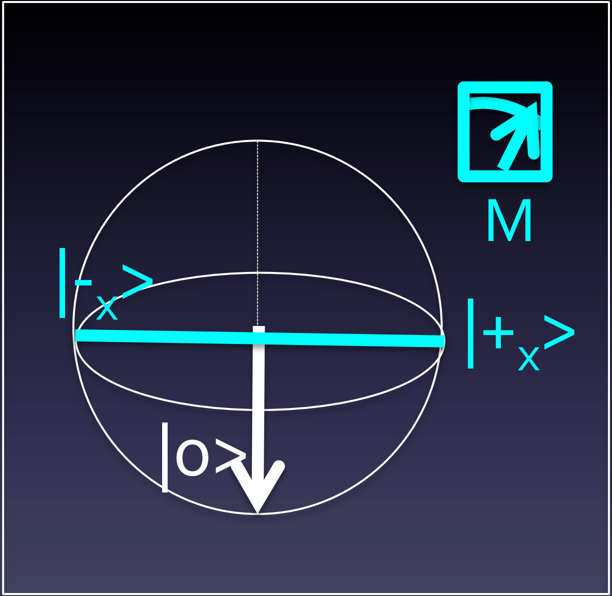
Meet the quantum heat (II)

System: a Qubit, $H=[h\nu_0/2]\ \sigma_Z$,
Transformation: (i) Preparation in $|0\rangle$ (ii) Measurement of $M=\sigma_x$



2 stochastic trajectories:

- $\Gamma_1 = [|0\rangle, |+_x\rangle]$
- $\Gamma_2 = [|0\rangle, |-_x\rangle]$

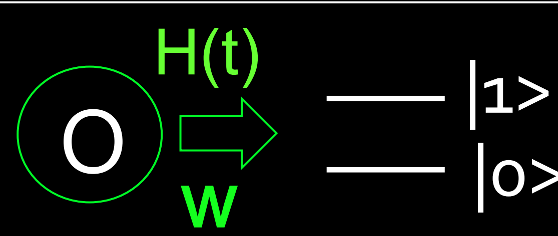
Energetic balance

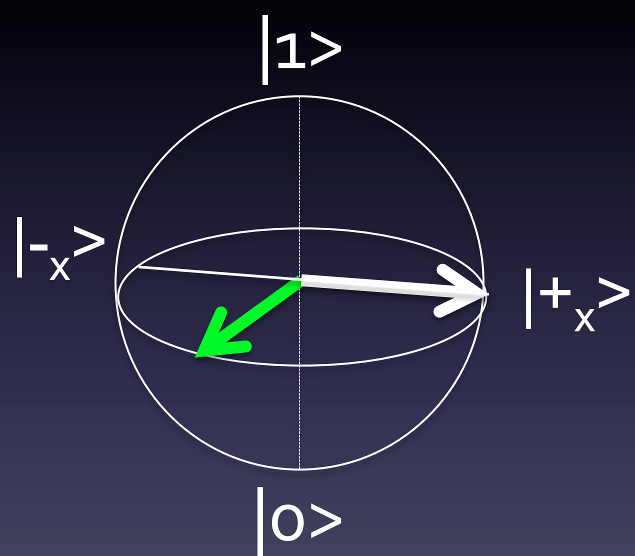
- Initial energy $U_i = - h\nu_0/2$
- Final energy $U_f = 0$
- $\langle \Delta U[\gamma] \rangle = h\nu_0/2 = \langle Q_q[\gamma] \rangle$

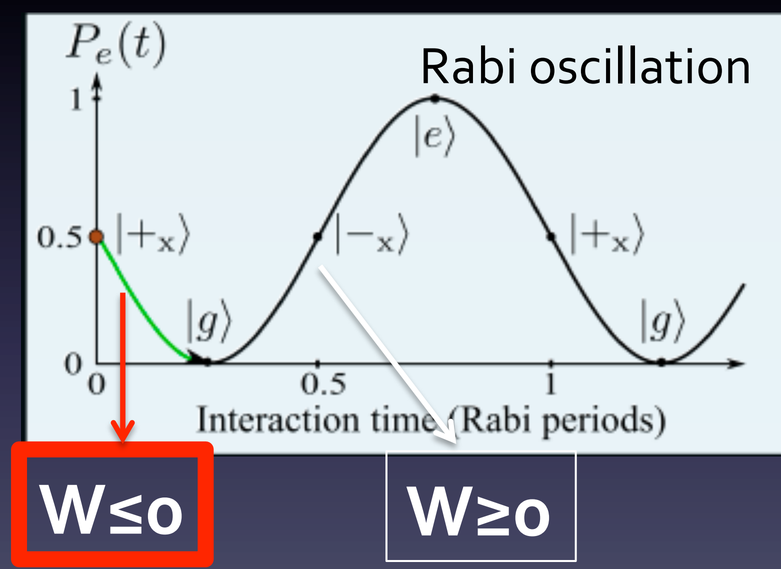
- $[M,H] \neq 0$ => Quantum heat is transferred **on average**
- **Let us use this property to build a quantum engine**

Basic mechanism

A qubit exchanges work with a resonant driving field



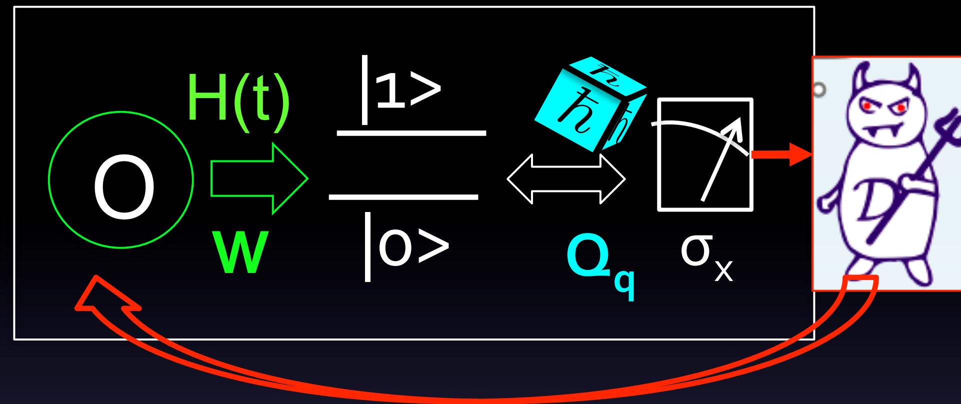




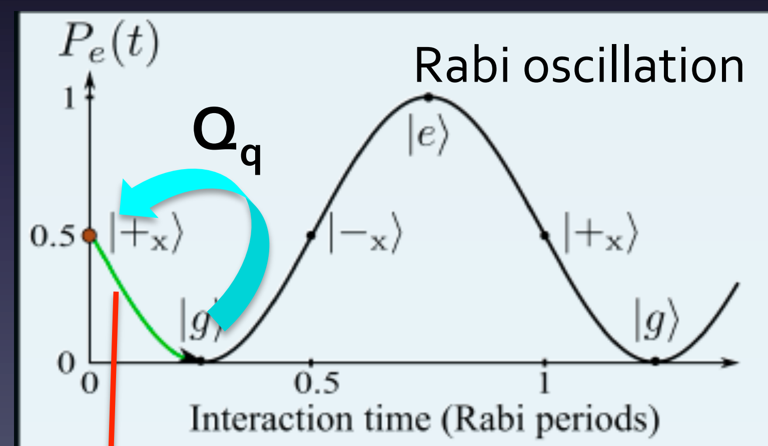
- $|+_x\rangle$ = good for work extraction ☺
- $|-_x\rangle$ = bad for work extraction ☹

Basic mechanism

- **Solution:** Stabilize the qubit in $|+_x>$
- Measurement of σ_X
- Feedback in $|+_x>$



- New quantum Maxwell's demon experiment
- Energy $<Q_q>$ is extracted from the measurement and converted to work $<W>$

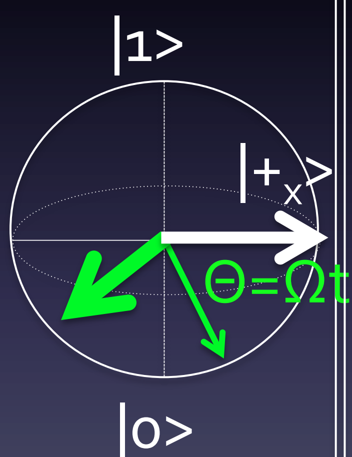


W≤0

Measurement powered engine (MPE)

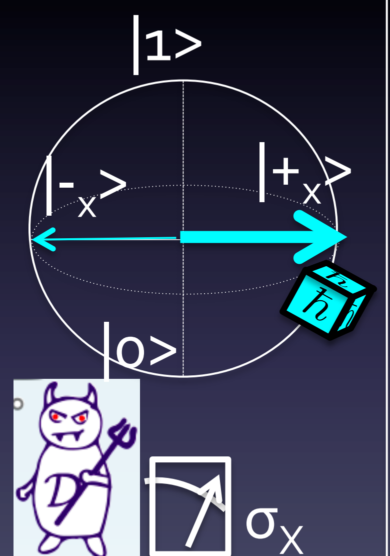
0. Initialize in $|+_x\rangle$, couple to a resonant field

1. Work extraction



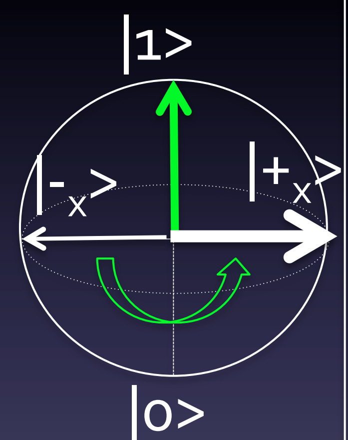
$W_{ext} = h\nu_0 \sin(\theta)/2$

2. Readout



$Q_q = h\nu_0 \sin(\theta)/2$

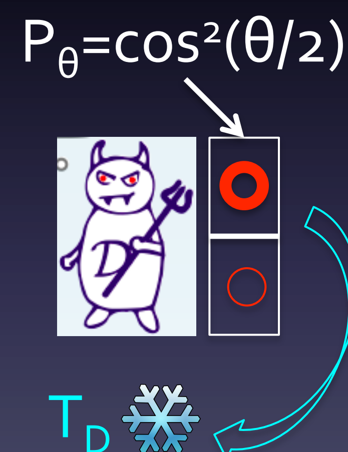
3. Feedback



$|-_x\rangle \rightarrow |+_x\rangle$

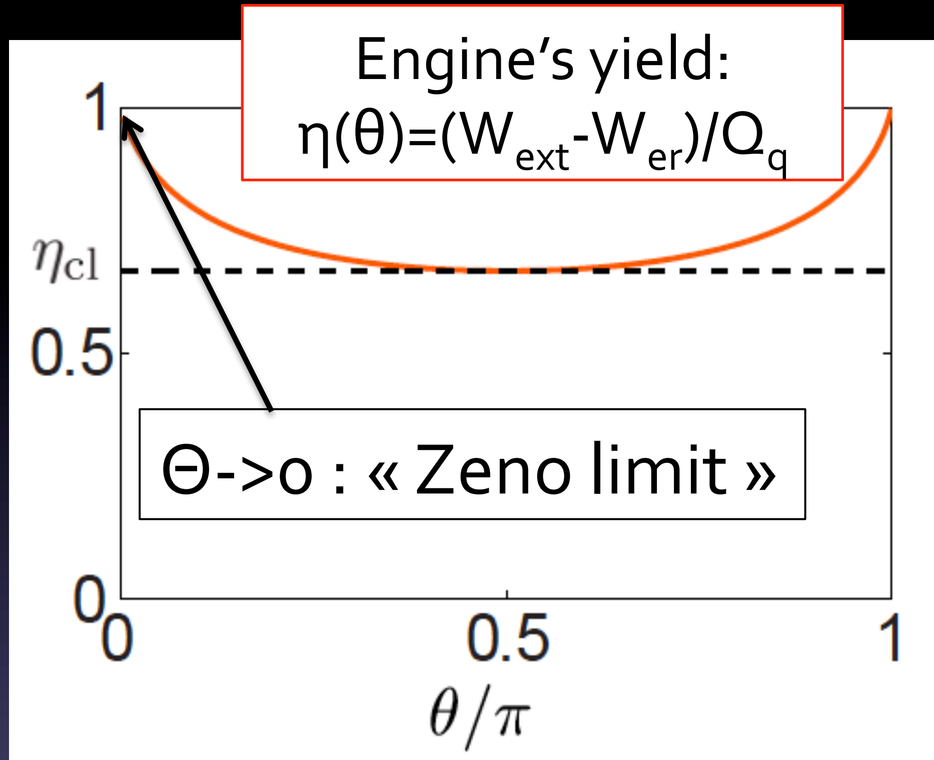
$W_{fb} = 0$

4. Memory erasure



$\langle W_{er}\rangle = T_D \cdot H_2[p_\theta]$

MPE performances: Yield



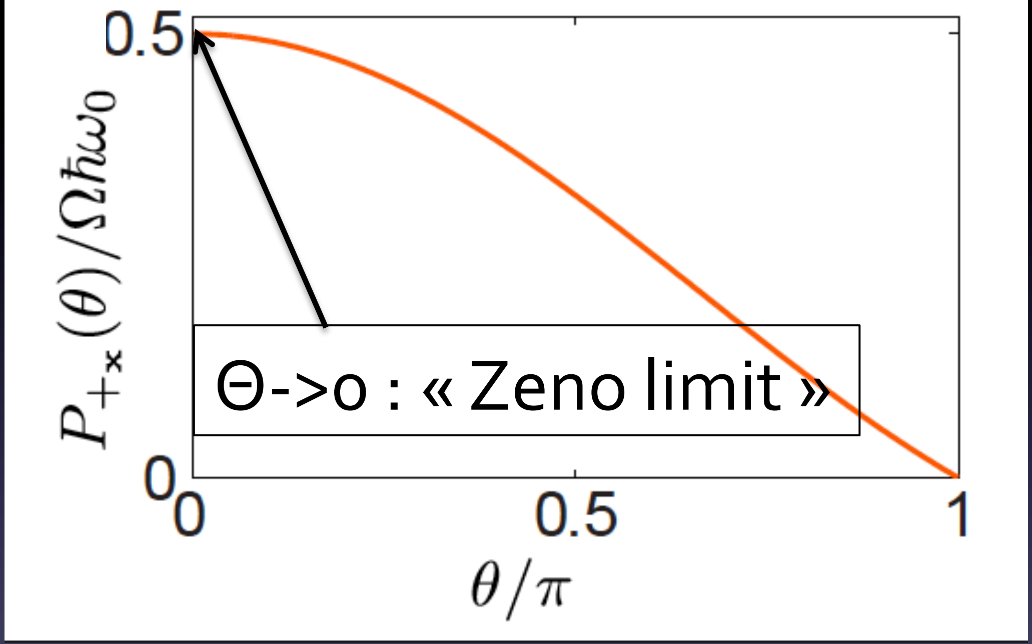
Zeno limit:

- Qubit « frozen » in the $|+_x>$ state ☺
- W_{ext} ->$h\nu_0\theta/2$; $W_{er} \approx \theta^2 \ln(\theta)$ => **Yield η->1**

Elouard et al, PRL 118, 260603 (2017)

MPE performances: Extracted power

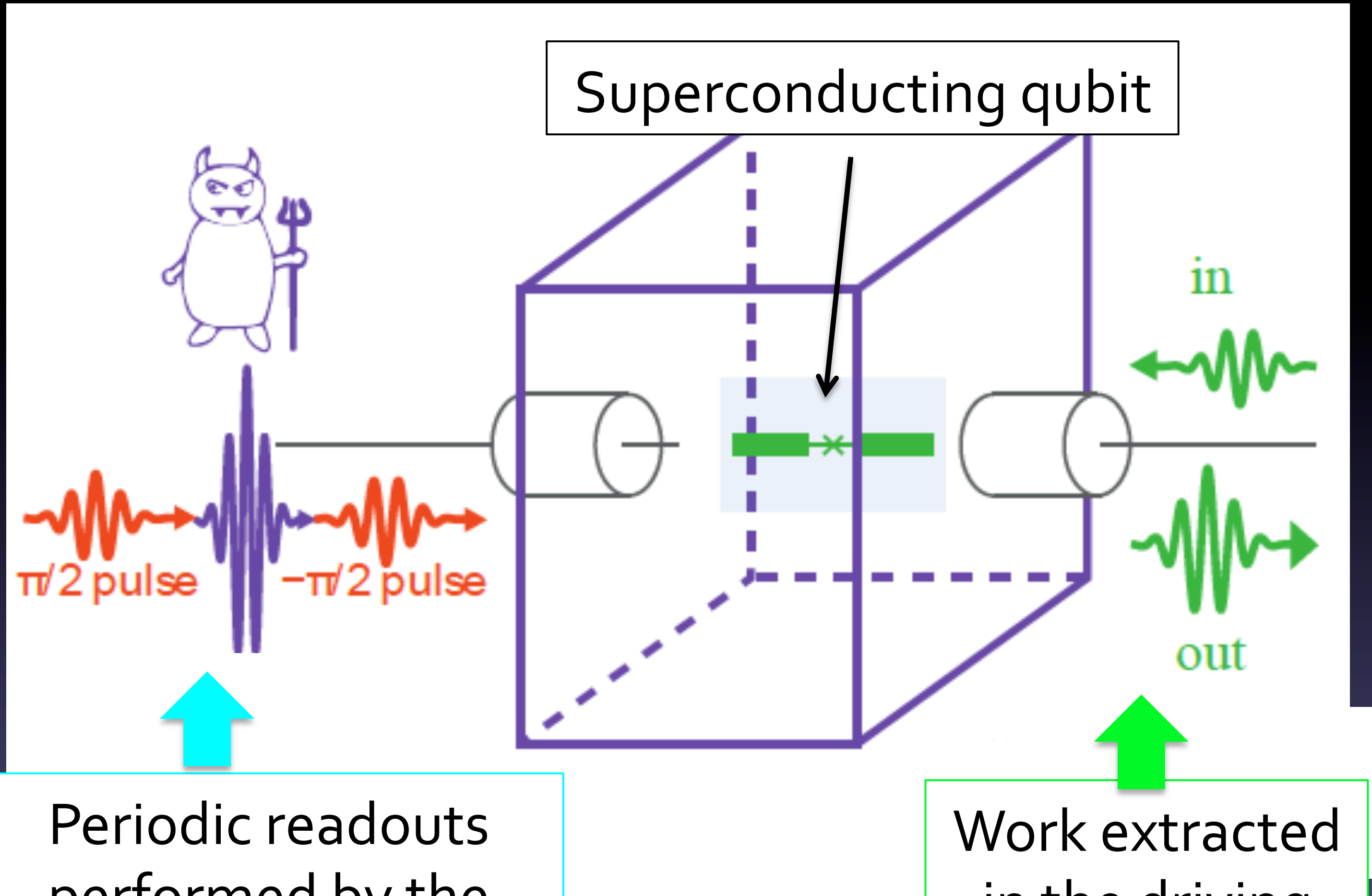
Extracted power
$P_{ext} = \Omega h\nu_o \sin(\theta)/(2\theta)$



Zeno limit: Qubit « frozen » in the $|+_x>$ state

- W_{ext}->$h\nu_o\theta/2$; $\theta=\Omega dt$, **$P \to P_{max} = \Omega h\nu_o/2$**
- **Power and yield simultaneously optimized**

Proposal for circuit QED

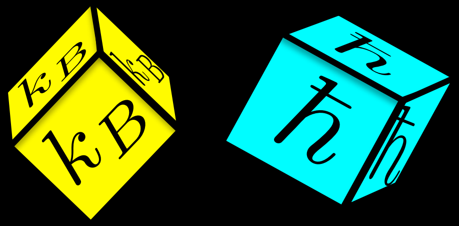


Periodic readouts performed by the demon

Work extracted in the driving field

Experiment still to come!

Outline



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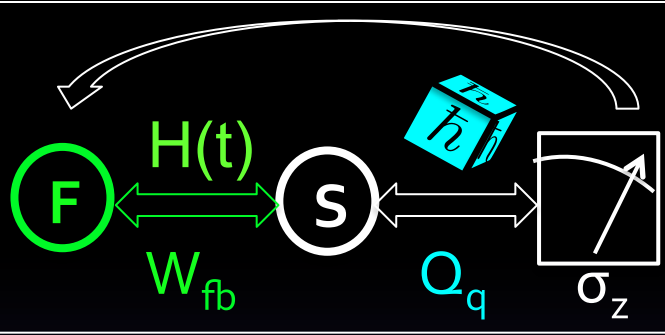
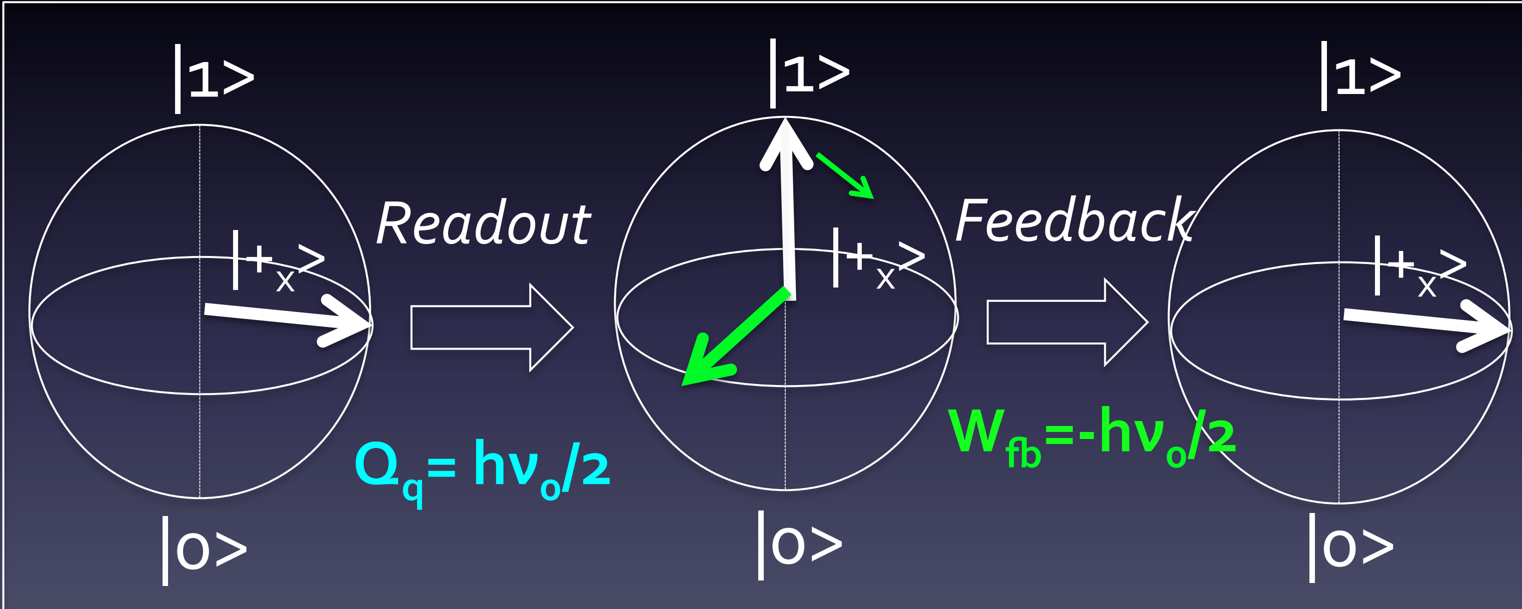
« Naïve » feedback stabilizing protocol

Goal: Stabilize $|\psi_i\rangle = |+_x\rangle$ against quantum noise using a feedback loop





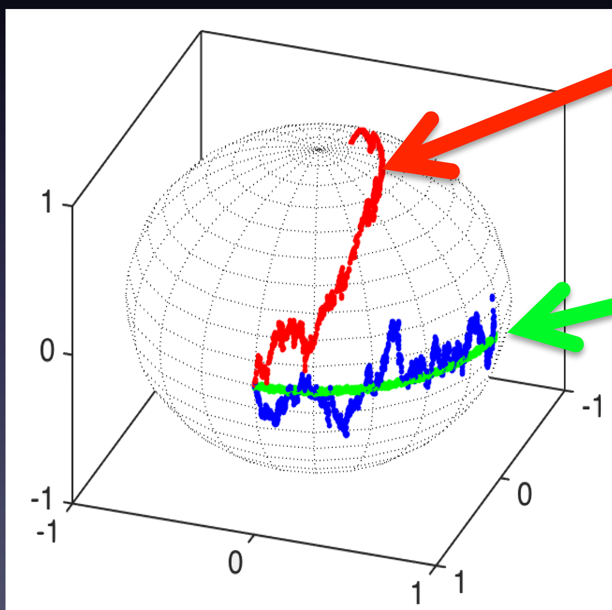
A perfect feedback requires
$W_{fb}\,[\Gamma] = -Q_q\,[\Gamma]$

A realistic feedback stabilizing protocol

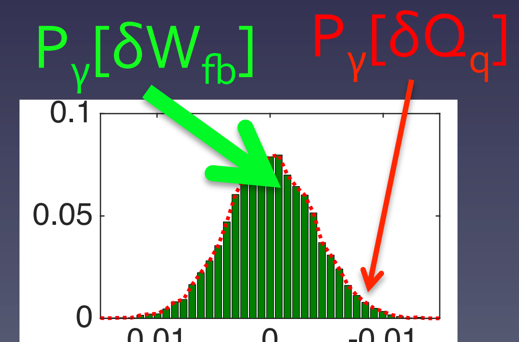
- Generalization of our framework to continuously monitored quantum systems with feedback loop
- Thermodynamic analysis of a stabilized qubit

No feedback => decoherence: γ converges towards |0> or |1>

Perfect feedback & stabilization



Histograms of quantum heat and work fluctuations



Elouard et al, npjQI 3:9 (2017)

A realistic feedback stabilizing protocol

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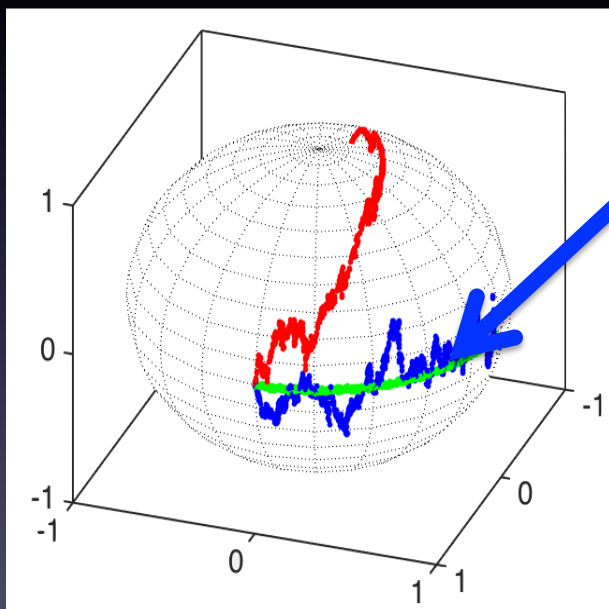
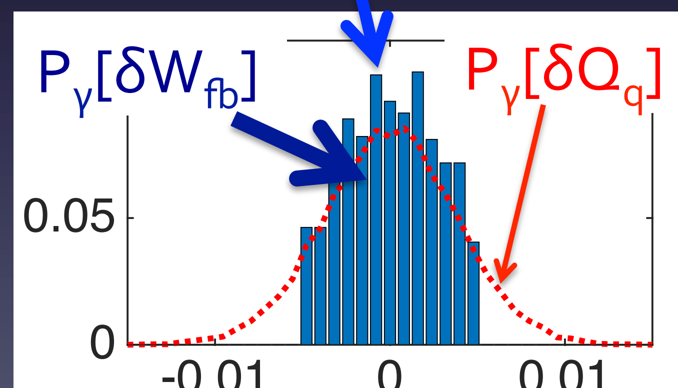
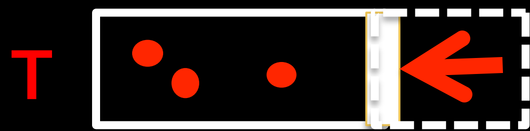


Power bounded feedback =>
Imperfect stabilization

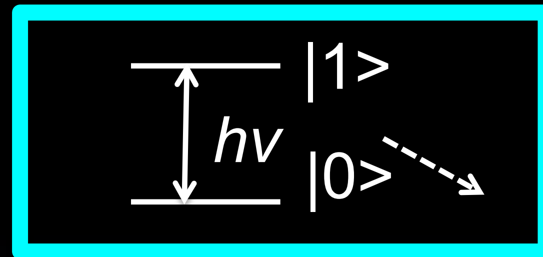


Elouard et al, npjQI 3:9 (2017)

Energetic cost of quantum control

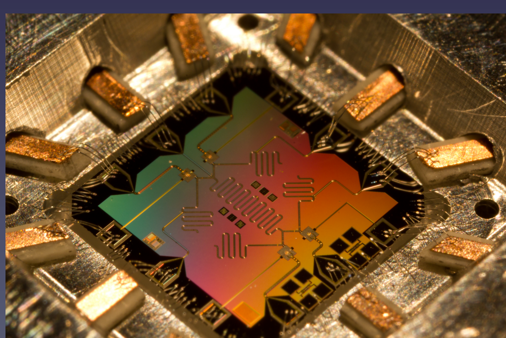


- Thermal noise
- Energy scale of classical control: kT

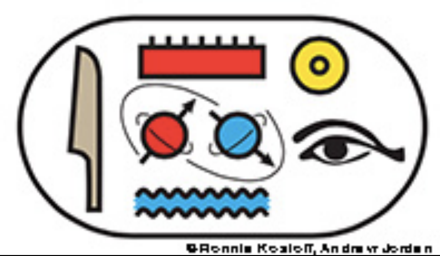


Cryostat

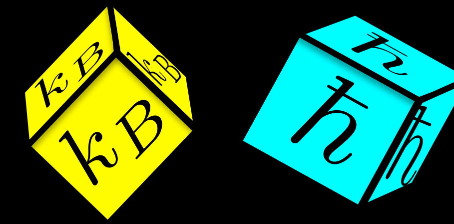
- Quantum noise: Pure dephasing
- $kT << hv$



Quantum heat: A new energy scale to assess the energetic cost of quantum control



Outline



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- **Thermodynamics of spontaneous emission**
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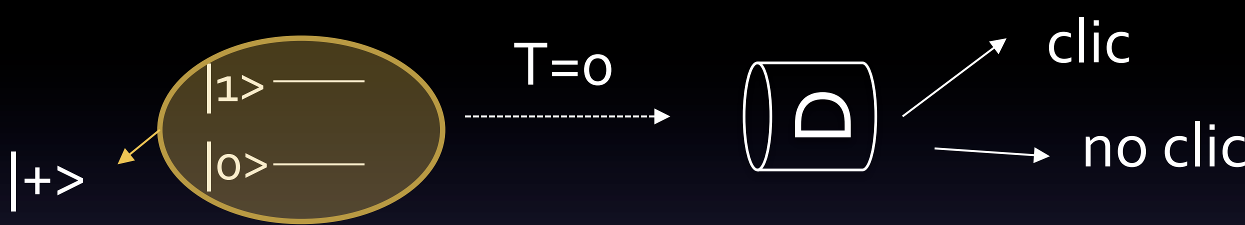
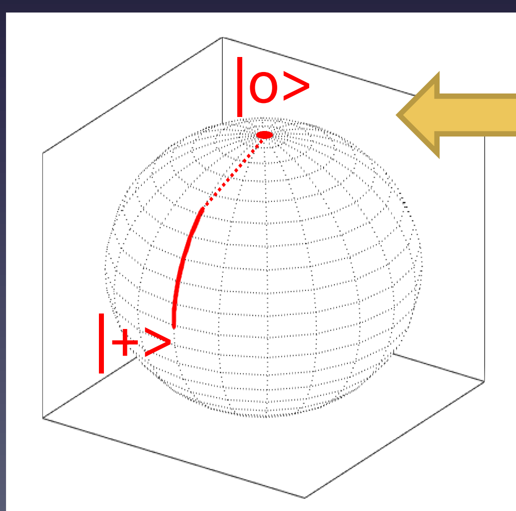
Scenery of spontaneous emission

- A Qubit prepared in |+> and coupled to a T=0 bath
- Quantum jump unraveling (Monitored by a photo-counter)



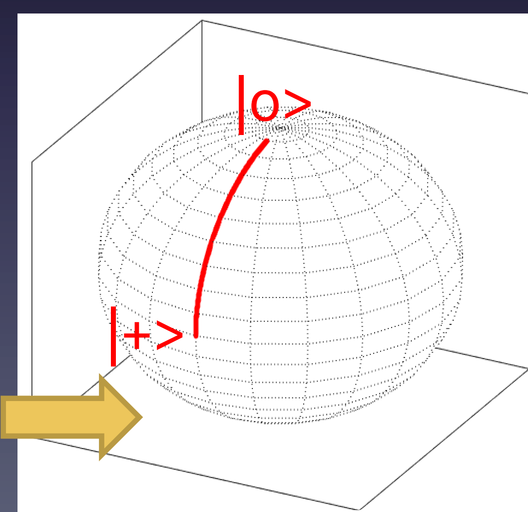
Clic => Jump

No clic => No-jump

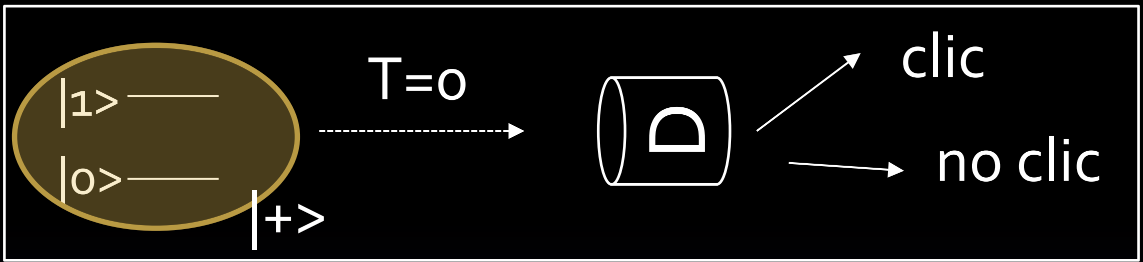


Destructive measurement in |1>

Destructive measurement in |0>



Thermodynamic analysis



- $\langle \Delta U[\gamma] \rangle = -h\nu_0/2$
- No work exchanged

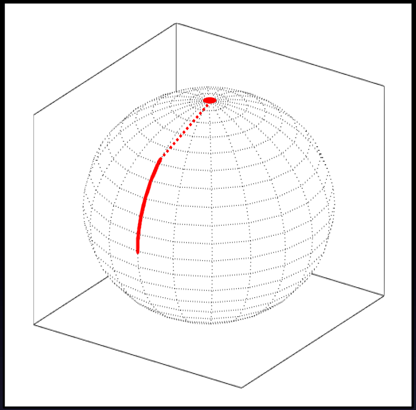
➢ **The bath plays a double role**

- Exchange of classical heat with the Qubit $Q_{cl} = 0$ or $- h\nu_0$
- Extraction of information on the Qubit's state => Quantum heat component Q_q

First Law: $\langle \Delta U[\gamma] \rangle = -h\nu_0/2 = \langle Q_q[\gamma] \rangle + \langle Q_{cl}[\gamma] \rangle$

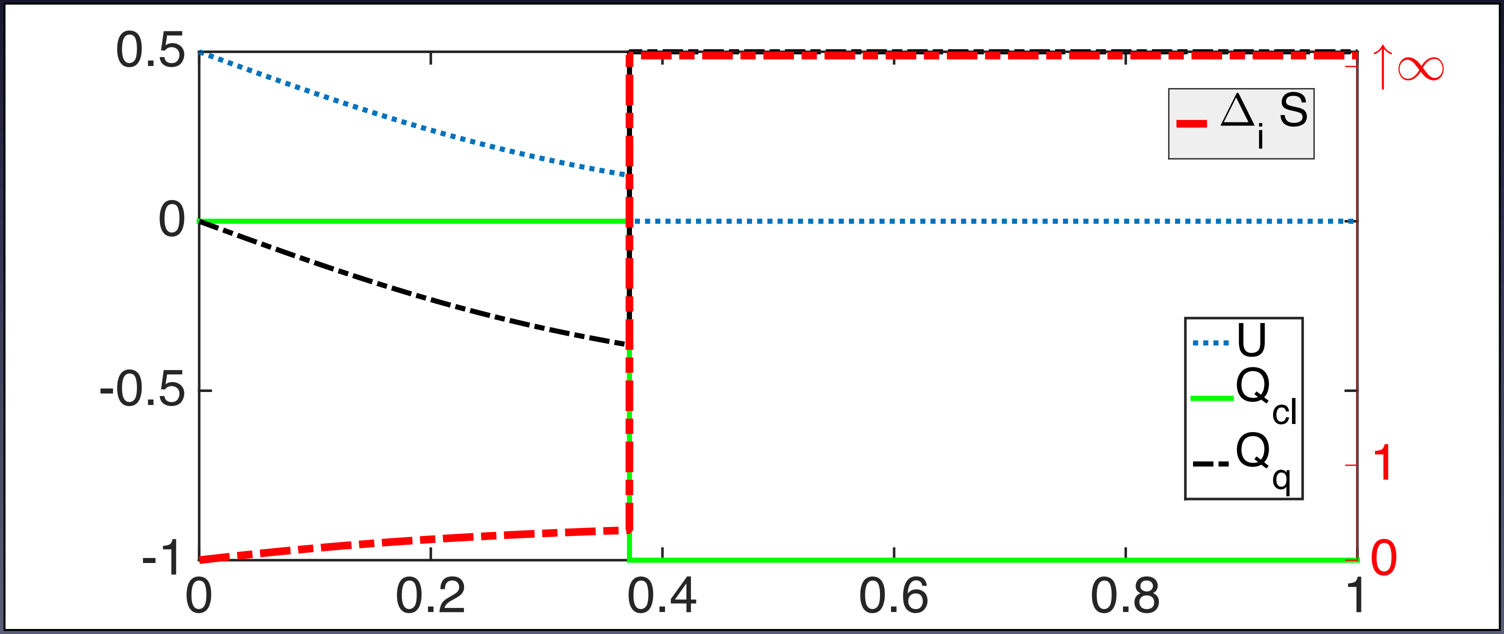
- Jump: $Q_{cl}[\gamma] = -h\nu_0$, $Q_q[\gamma] = h\nu_0/2$ (measurement in |1>)
- No-Jump: $Q_{cl}[\gamma] = 0$, $Q_q[\gamma] = -h\nu_0/2$ (measurement in |0>)

Jump trajectories

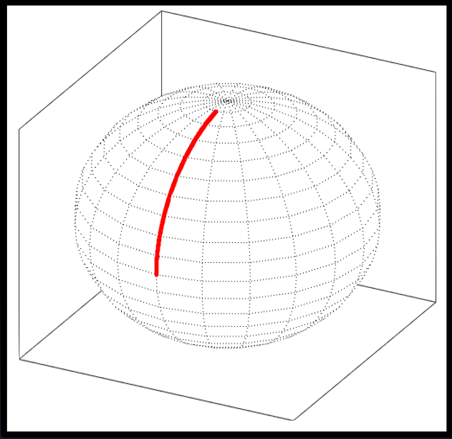


After the jump:

- Entropy production diverges
- Classical heat Q_{cl} = -hω$_o$
- Quantum heat Q_q = hω$_o$/2

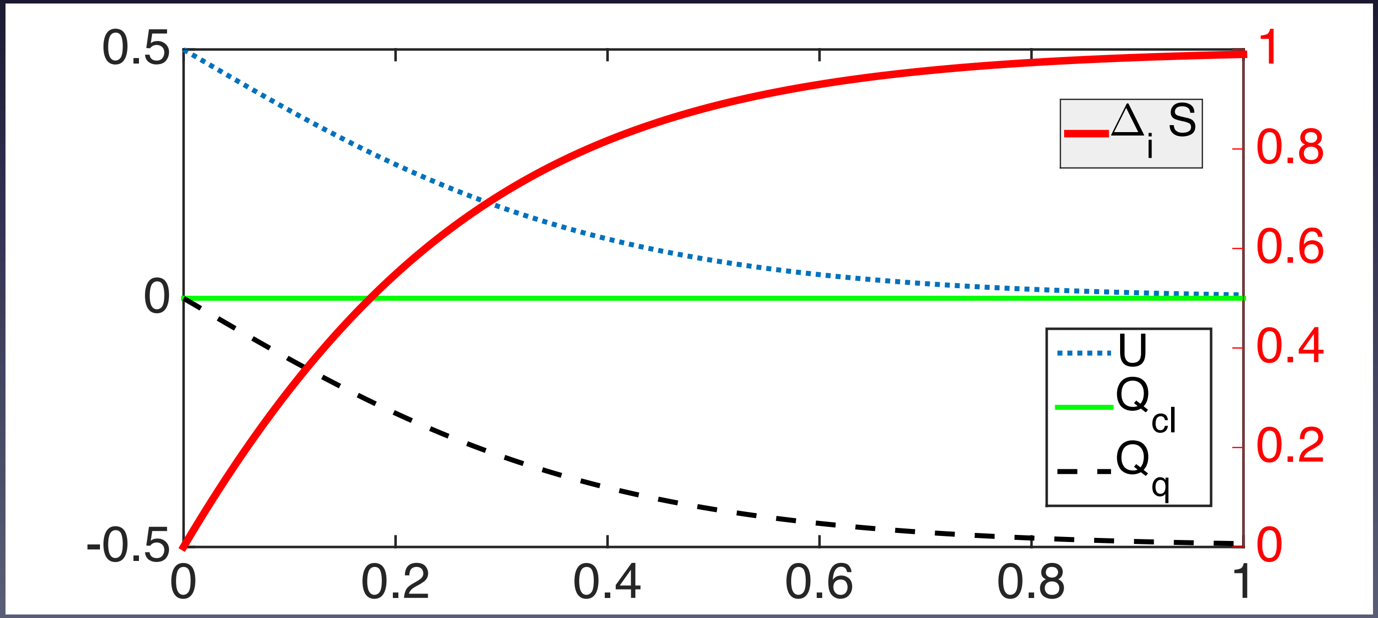


No jump trajectories

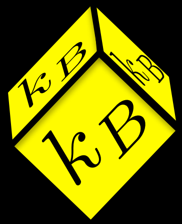


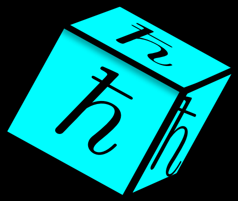
For t large

- Classical heat $Q_{cl} = 0$
- Quantum heat $Q_q = -h\omega_0/2$
- Entropy production $\Delta_i S = \Delta S_{VN}$
- Entropy of measurement



Conclusions

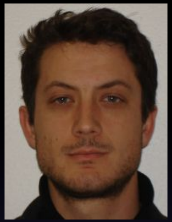




- Energetic footprint of quantum noise: Quantum heat => Proper energy scale to assess the work cost of quantum control
- Work extraction from quantum noise instead of thermal noise => **Measurement Powered Engine**
- Doable with state of the art devices of cQED
- Key role of randomness in the building of thermodynamical concepts

Outlooks & collaborations

Quantum engines



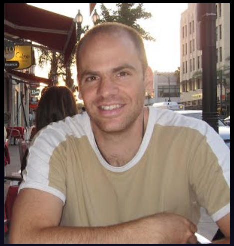
M. Richard, Grenoble

B. Huard, Lyon

Thdyn of entanglement

G. Haack Geneva

Thdyn of fluorescence



M. Esposito Luxembourg

J. Anders Exeter

Quantum energetic bounds

C. Elouard Rochester

D. Herrera-Marti Grenoble

J. Monsel, Grenoble

Thermodynamics of reservoir engineering

M. Santos Rio

D. Gerace Pavia

A.Carvalho Brisbane

Quantum foundations

P. Grangier, Orsay & N. Farouki, Grenoble

- **25** interdisciplinary PhD scholarships for quantum engineering in Grenoble along 4 calls (2017-2018)
- Next and LAST deadline: October 2018

QuEnG PhD. Program 2017
Call for Application

Interdisciplinary PhD program "Quantum Engineering Grenoble"

We invite outstanding candidates to apply for our three-year interdisciplinary PhD program "Quantum Engineering Grenoble" (QuEnG). The QuEnG program aims to foster a local ecosystem for quantum technologies, building on the unique concentration of expertises, know-how, and resources of Grenoble area. The targeted ecosystem will connect various areas of knowledge, from science to humanities and entrepreneurship. The students of the program will work together to address current challenges of quantum technologies, at the interface between physics, computer science, mathematics, industry, philosophy and social science. They will contribute to the creation, the development and the animation of the ecosystem through actions supported by Grenoble-Alpes University. The QuEnG program provides a unique opportunity to develop a network both in the private and in the academic sector, and to become one of the future quantum engineers.

Description

10 PhD scholarships will be attributed on the following topics:

- **Quantum hardware:** up to 3 scholarships (Interface Physics/Computer Science and/or industrial coaching)
- **Quantum software:** up to 2 scholarships (Interface Computer Science/Physics)
- **Qubit/photon interface:** up to 1 scholarship (Interface Physics/Mathematics and/or with industrial coaching)
- **Quantum sensing:** up to 1 scholarship (Physics with industrial coaching)
- **Quantum energetics:** up to 2 scholarships (Interface Physics/Mathematics, and/or with industrial coaching)
- **Societal and philosophical aspects of quantum theory and quantum technologies:** up to 2 scholarships (Philosophy of Physics or Social sciences embarked in a Physics laboratory)

Salary

out teaching) to 2100 euros/month (with teaching) before taxes
n 5 k€ to 40 k€

main criteria:
ster's degree or equivalent qualification
knowledge in Quantum Computing, Quantum Technology, Philosophy or
matics

017, 11:59 am CET

ww.grenoble-lanef.fr/spip.php?article164

grams is enlarged with three other funding possibilities which bear te of them.

ciences
→ PhD program LANEF
→ PhD program GreQue

UNIVERSITÉ Grenoble Alpes

2017 PhD. Program
Quantum engineering
In Grenoble

Quantum engineering is a novel domain of research, built on fundamental research carried out in the last 20 years all over the world. Quantum technologies offer radically new materials and devices for the next century, in sectors such as security, energy, communications, or healthcare. To transform such disruptive scientific concepts into real life benefits it is crucial to develop research aiming at higher technology readiness levels. To ensure that Europe takes the leadership in this coming quantum revolution, we must train next generation quantum engineers, by offering doctoral training in interconnected domains with the highest scientific standards, while equally providing an opening to the industrial world.

Grenoble is world renowned for its fundamental research institutes in condensed matter physics, nanosciences, computer sciences & mathematics as well as its high-tech innovative companies ranging from local start-ups to multinational groups. Grenoble area hosts 25 000 academic and industrial researchers, and more than 60 000 students. Grenoble's ecosystem is ranked within the top 5 innovative cities in nanotechnologies worldwide and 1st in Europe.

Grenoble Quantum Engineering (GreQuE) novel Doctoral Programme will grant 25 PhD projects hosted in Grenoble research institutes in which each student will benefit from a 2 to 6 months placement in a European company. 17 SMEs & large groups in 5 countries have committed to offer such placement to our students in accordance with their PhD project.

The topics include experimental and theoretical aspects of:

- **Nanoelectronics,**
- **Superconductive Qubits,**
- **Spintronics,**
- **Photonics,**
- **Computer science.**

How to apply:
GreQuE Doctoral Program is funded by the Europ
Slodowska-Curie Actions (MSCA). Applicants must
No nationality conditions, but applicants must not h
France during the last three years.

Salary: 1758 €/month before taxes during three year

Candidates are invited to visit the GreQuE webpage
http://www.grenoble-lanef.fr/spip.php?article171 and
greque@neel.cnrs.fr

Deadline to submit your application: 2017, April 10, 11:59 am (CET)

The 2017 call of the PhD programs is enlarged with three other funding possibilities which bear particularities. You must take note of them.

→ PhD program Fondation Nanosciences
→ PhD program LANEF
→ PhD program QuEnG

quantum.univ-grenoble-alpes.fr