A short story of quantum and information thermodynamics

Alexia Auffèves

Institut Néel - CNRS & Université Grenoble-Alpes

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Outline

- Thermodynamics, from classical to quantum
- Thermodynamics of quantum measurement
- Measurement-powered quantum engines
- Application to quantum information technologies

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- **Thermodynamics, from classical to quantum**
- Thermodynamics of quantum measurement
- Measurement-powered quantum engines
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Macroscopic thermodynamics

Batteries, operators… | System « Working substance » | Baths

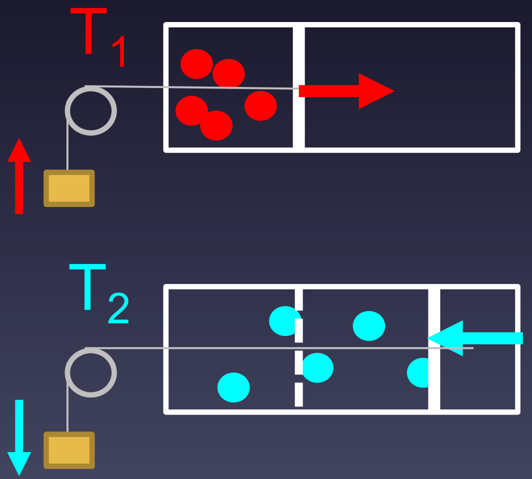
O ⟺ *Work* ⟺ S ⟺ *Heat* ⟺ 

- Engines (*or how turning lead into gold*)
- 1^{st} Law

- Irreversibility, fundamental bounds, no-gos
- 2^{nd} Law

Kelvin Planck no-go

➢ « One cannot extract work continuously from a single hot source »



$$W_1 = -T_1 \Delta S$$
$$W_1 \leq 0$$

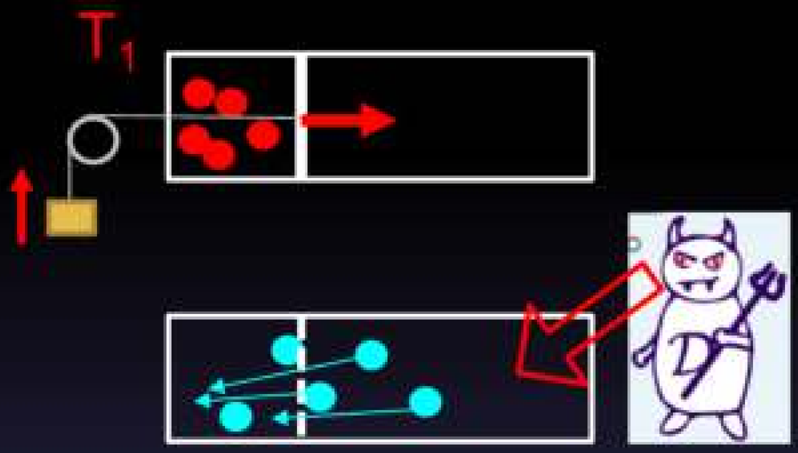
$$W_2 = -T_2 \Delta S$$
$$W_2 \geq 0$$

Carnot engine

➢ Work extraction = Expansion in a hot source

➢ **Need to reset =** Compression in a cold source

Maxwell's demon paradox

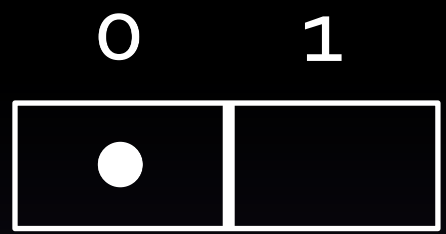


Maxwell's demon

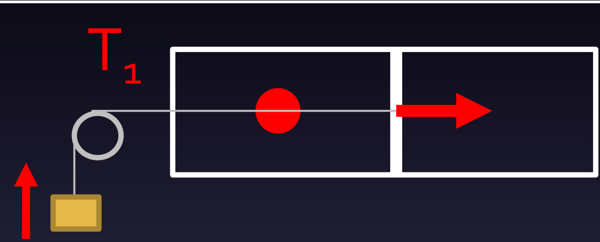
- Use information to reset the engine at no work cost
- Violation of the second Law?

- **Resolution of the paradox**
- « Information is physical » Landauer 1961 + Bennett, Szilard…
- Need to erase the demon's memory to close the cycle

Information thermodynamics

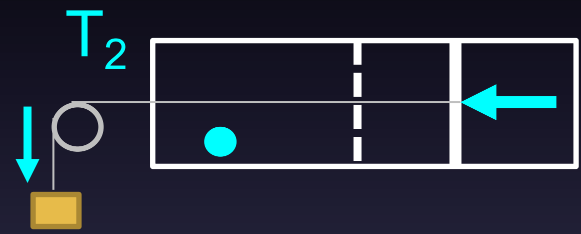


- 1 bit of memory 0,1 is the working substance
- New interpretation of Carnot engine



$$W_1 = -k\ln(2)T_1$$

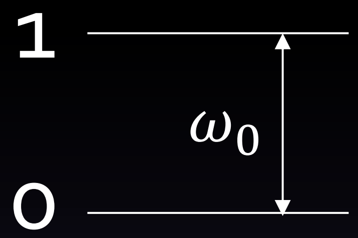
Szilard engine



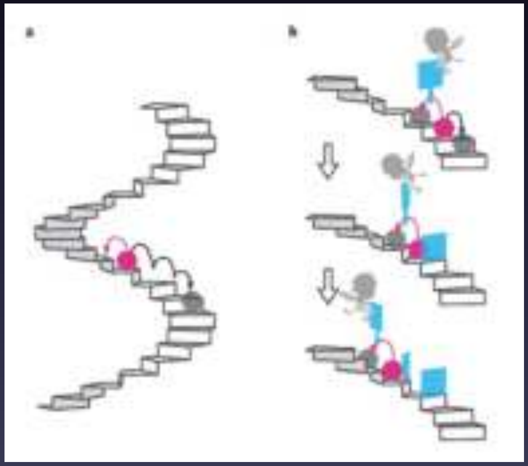
$$W_2 = k\ln(2)T_2$$

Landauer's erasure work

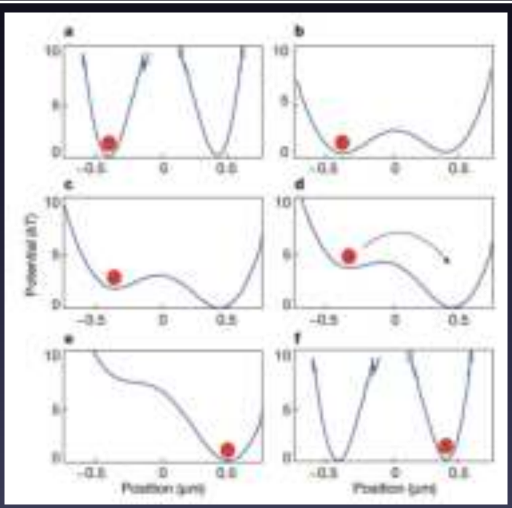
Information thermodynamics



- A more realistic realization of a « bit of memory »

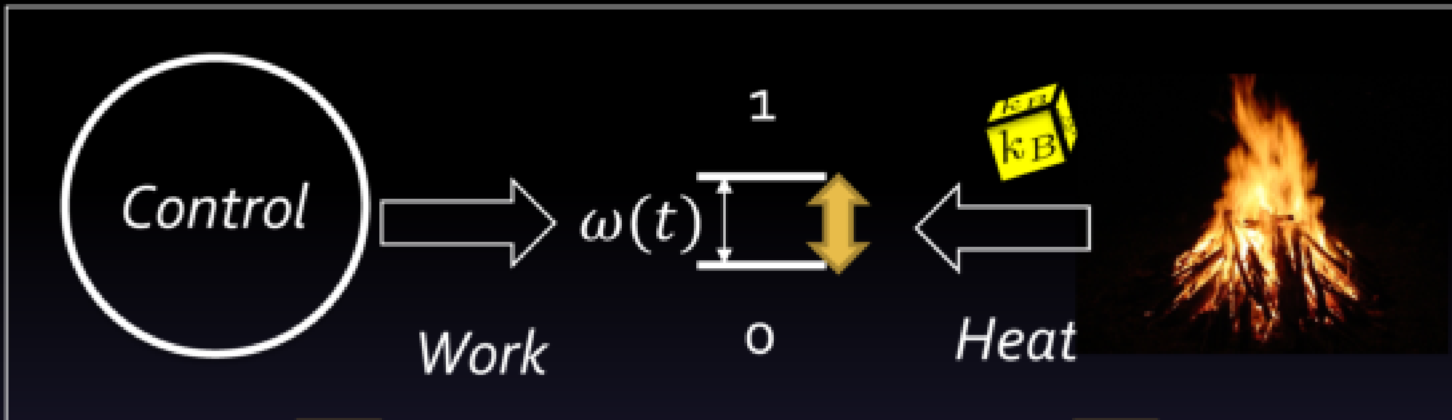


- Toyabe, Ueda, Sano, Nature Physics 2011
- Information induced rectification



- Ciliberto, Lutz, Nature 2011
- Readout of Landauer's erasure work

Stochastic thermodynamics

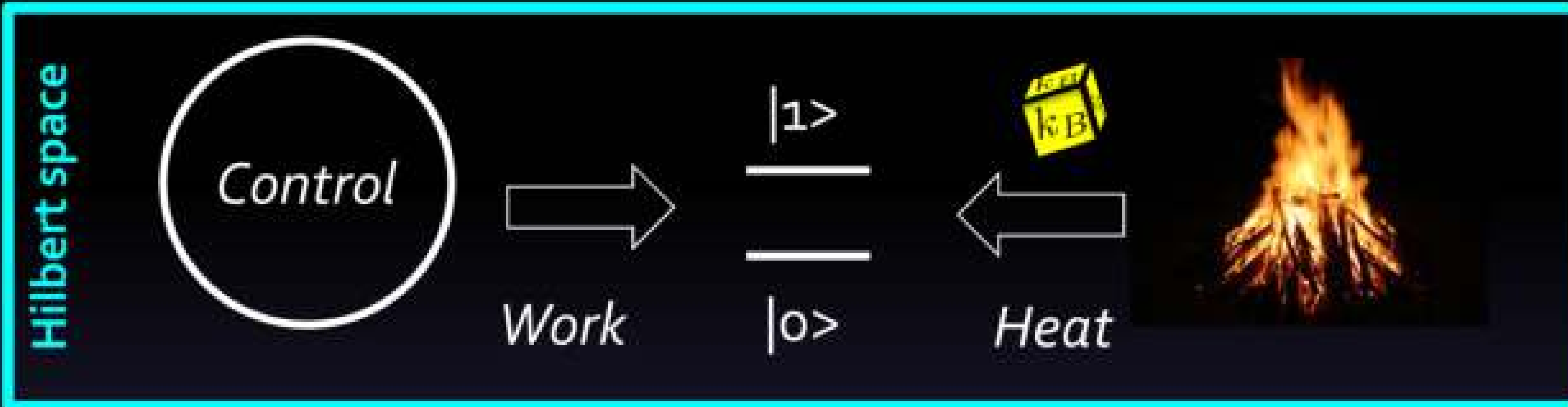


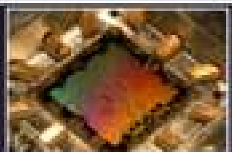
Work extraction from **thermal** fluctuations
⇒ Nano engines
⇒ Information engines

Thermal fluctuations =>
Lack of control
Irreversibility &
Fundamental bounds

« Stochastic » thermodynamics is based on randomness

Quantum thermodynamics?



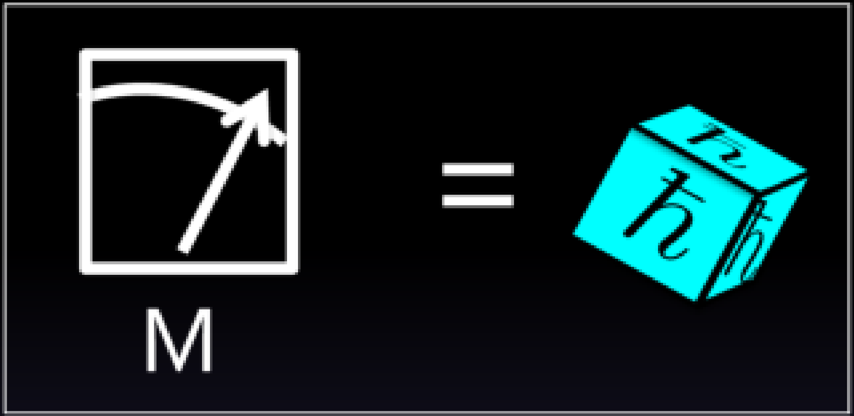


- Do quantum engines outperform classical engines?
- Work cost of quantum computation?
- Quantum Maxwell's demons?
- Quantum irreversibility?…

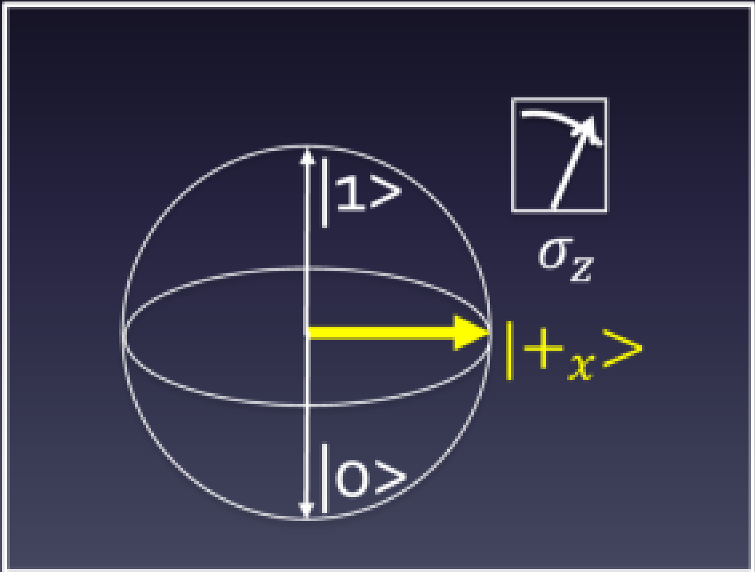
Outline

- Thermodynamics, from classical to quantum
- **Thermodynamics of quantum measurement**
- A measurement-powered quantum engine
- Application to quantum information technologies

Measurement: The ultimate dice



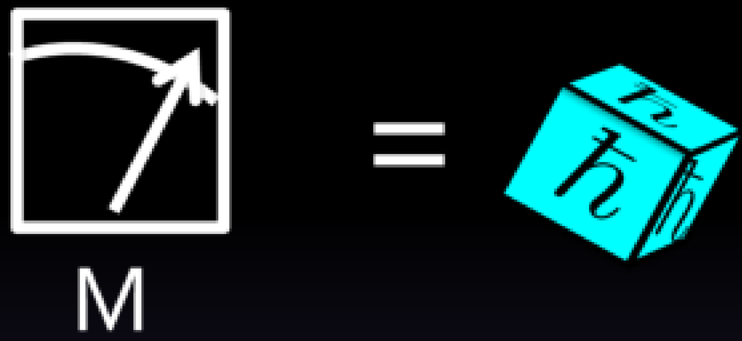
- Quantum measurement perturbs the system's state
- The perturbation is random
- **Quantum fluctuations**



Example

- Initial state:
- $|+_x> = (|0> + |1>)/\sqrt{2}$
- Measurement « along z »
- The qubit is either projected on |0> or |1>
- Probability P(0)=P(1)=1/2

Measurement: The ultimate dice



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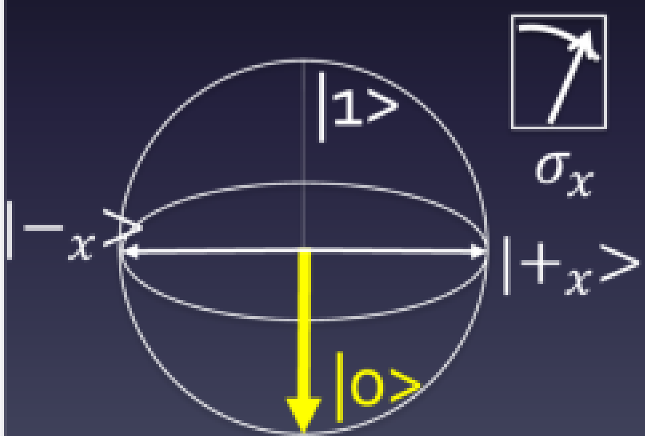
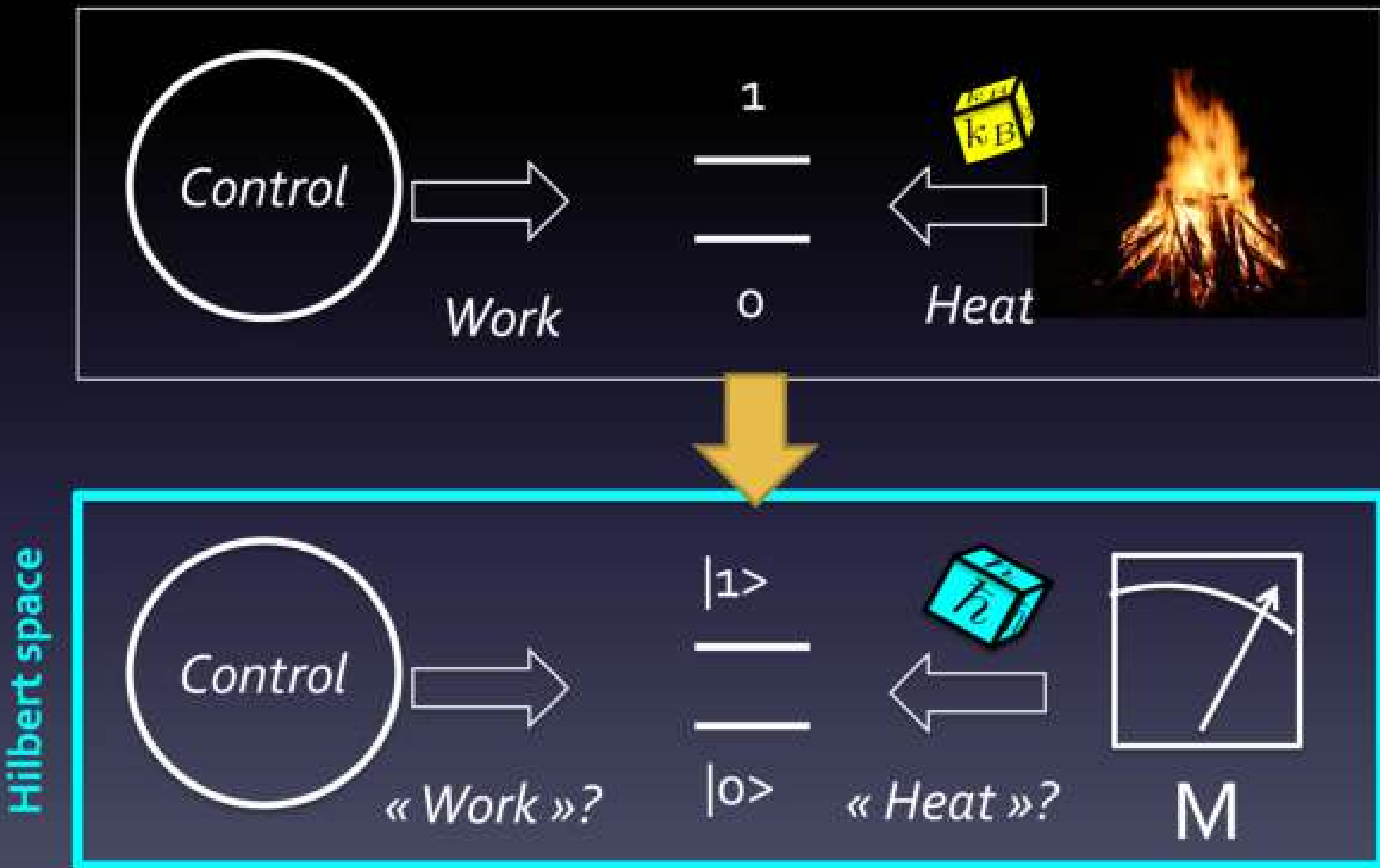


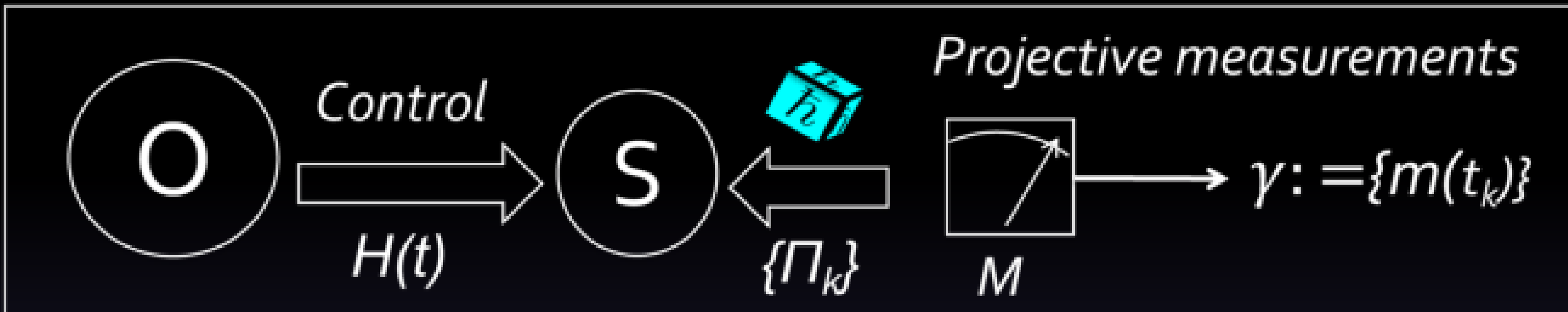
Example

- Initial state:
- $|0> = (|+_x> + |-_x>)/\sqrt{2}$
- Measurement « along x »
- The qubit is either projected on $|+_x>$ or $|-_x>$
- Probability P(+)=P(-)=1/2

Rebuilding thermodynamics on quantum measurement

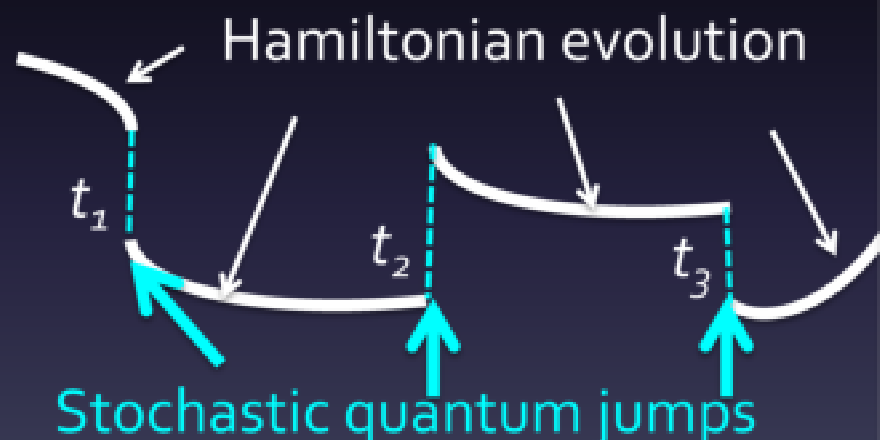


Scenery and definitions



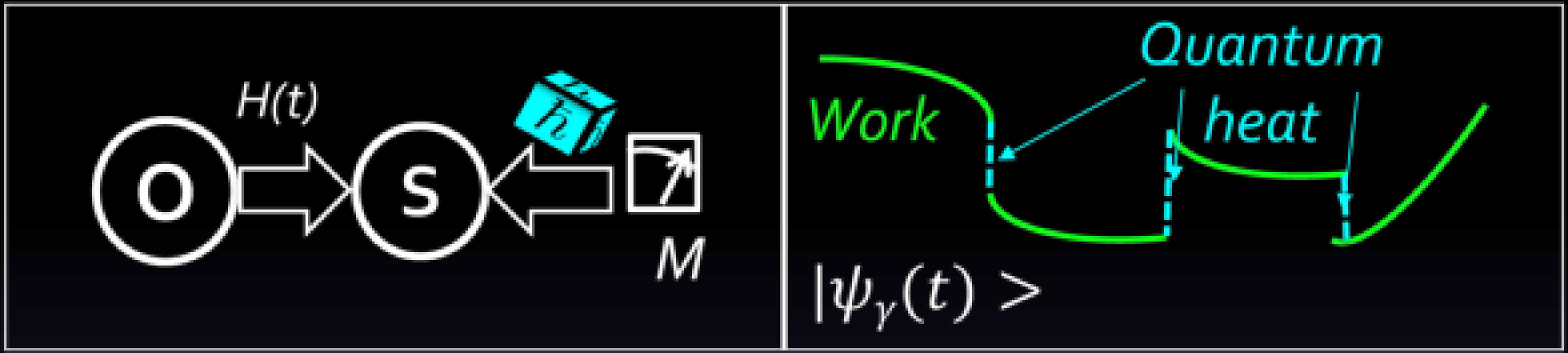
- Pure initial state $|\psi(t_0)>$
- Read measurement outcomes:

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



- Internal energy: $U_\gamma(t) := < \psi_\gamma(t)|H(t)|\psi_\gamma(t) >$

First Law

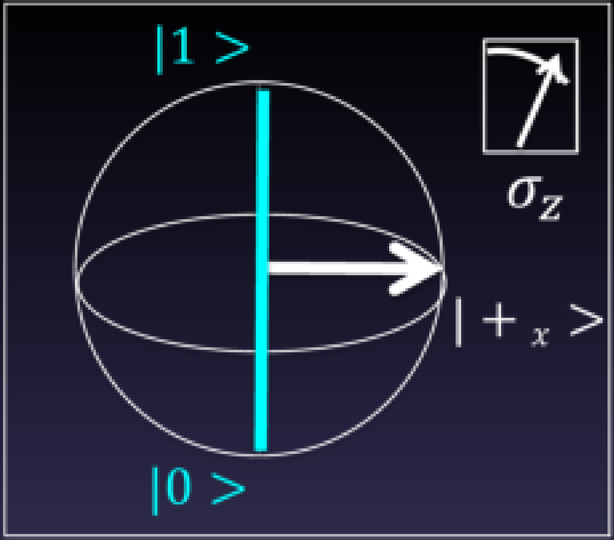


- **Work** is exchanged during the continuous (unitary) evolutions. Deterministic energy exchange with the controlling device
- **« Quantum heat »** is exchanged during the quantum jumps. Stochastic energy exchanges induced by quantum measurement.
- 1st Law guaranteed by construction
- $\Delta U_\gamma = W[\gamma] + Q_q[\gamma]$

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

Example 1

System: a Qubit, H=[$h\nu_0/2$] σ_Z,
Transformation: (i) Preparation in $|+_x>$ (ii) Measurement of σ_z



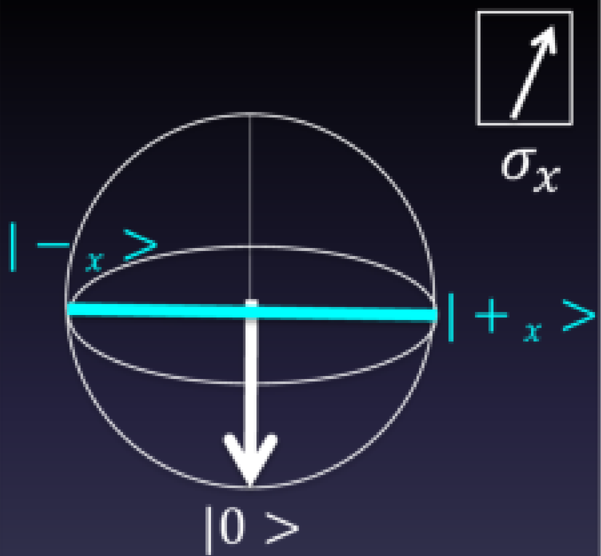
2 « stochastic trajectories »:
- $\gamma_1 = [|+_x>, |0>]$
- $\gamma_2 = [|+_x>, |1>]$

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

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

Example 2

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



2 stochastic trajectories:

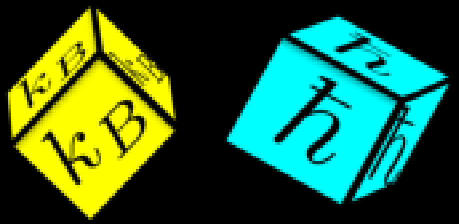
- $\gamma_1 = [|0>, |+_x>]$
- $\gamma_2 = [|0>, |-_x>]$

Energetic balance

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

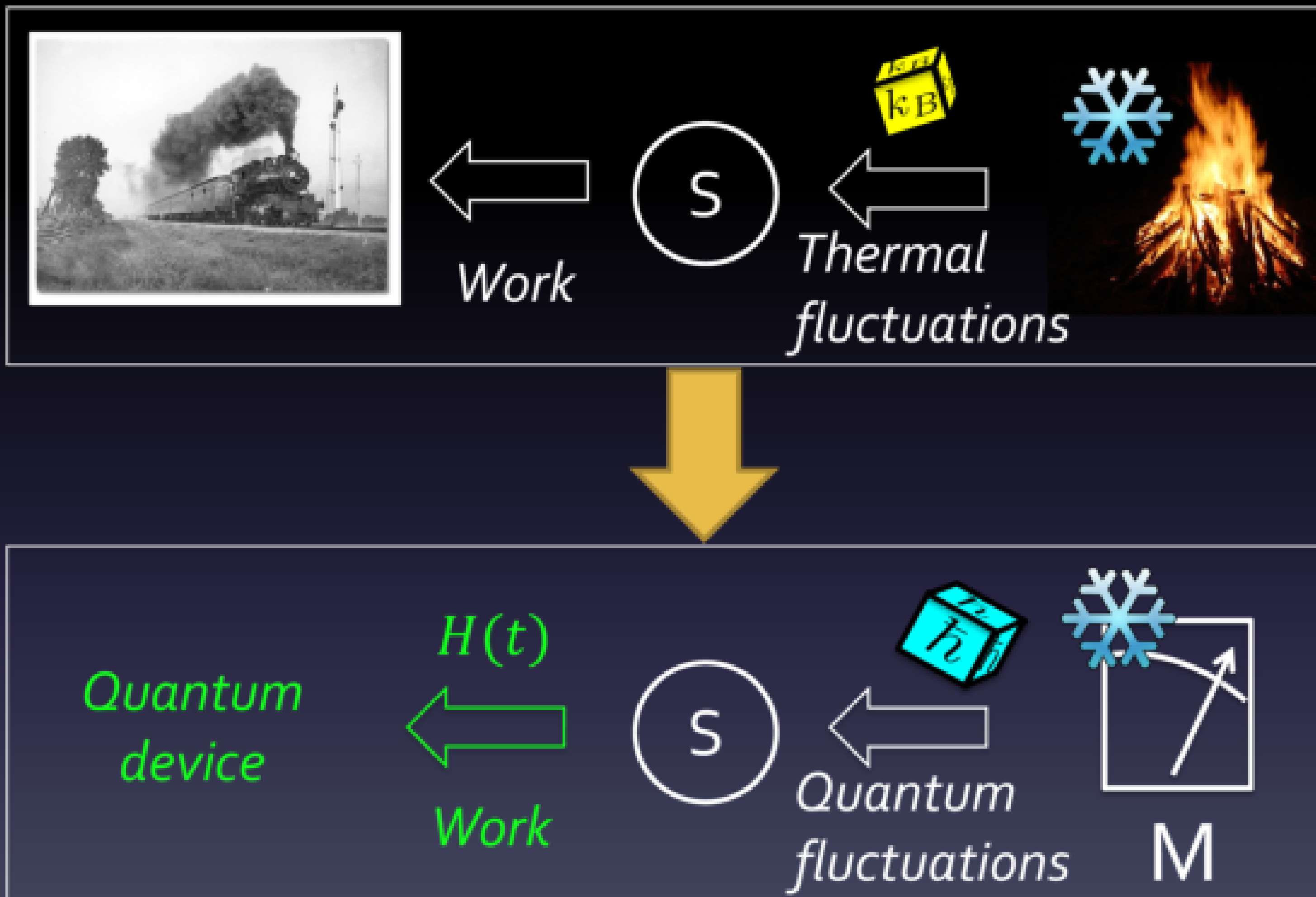
- $[M, H] \neq 0$ => Quantum heat is transferred **on average**
- **Let us use this property to build a quantum engine**

Outline



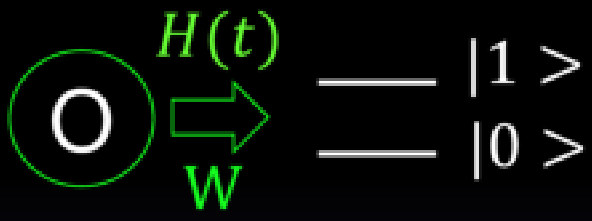
- **➢** Thermodynamics, from classical to quantum
- **➢** Thermodynamics of quantum measurement
- **➢** **Measurement-powered quantum engines**
- **➢** Application to quantum information technologies

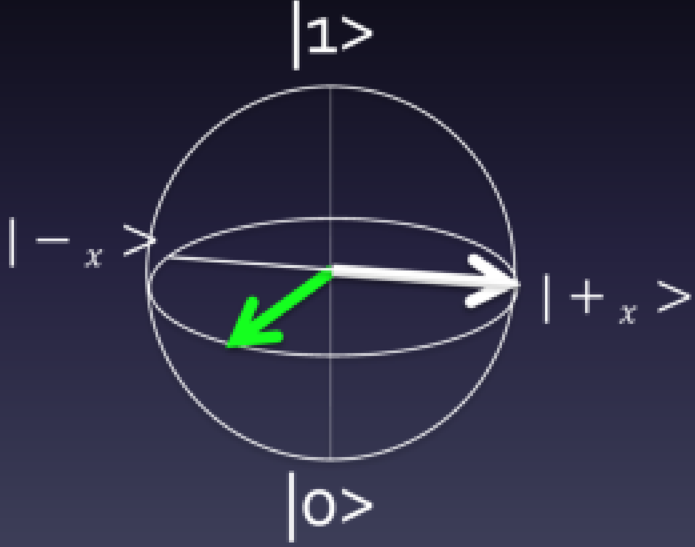
The strategy

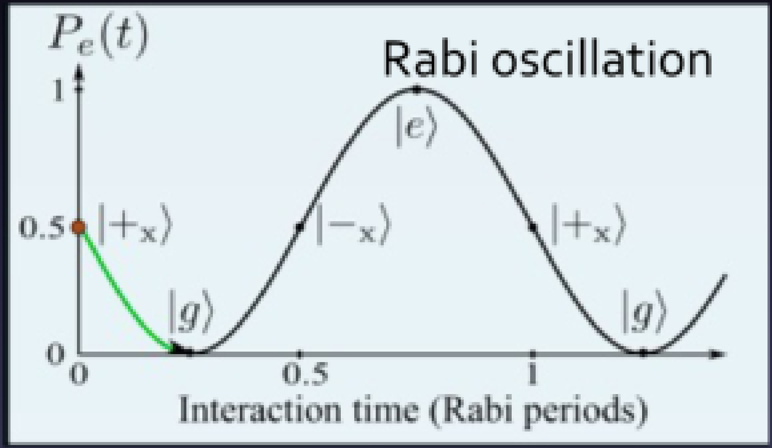


Rabi oscillation

A qubit coupled to a resonant field:
Coherent and reversible energy exchange between the qubit and the field = **« Rabi oscillation »**



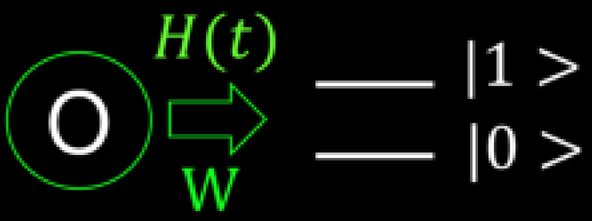


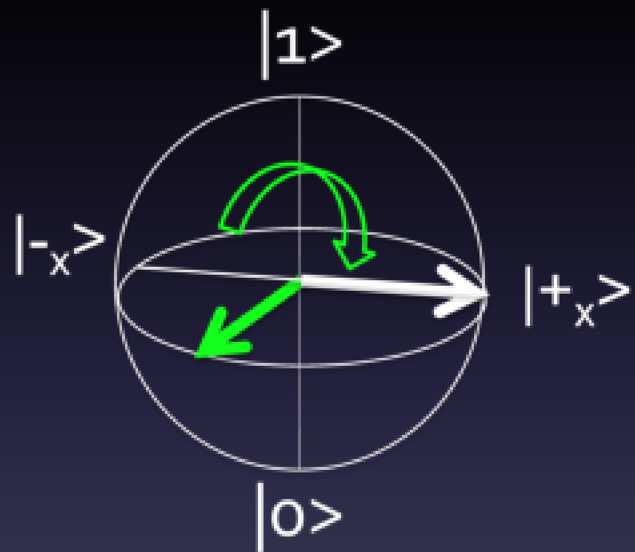


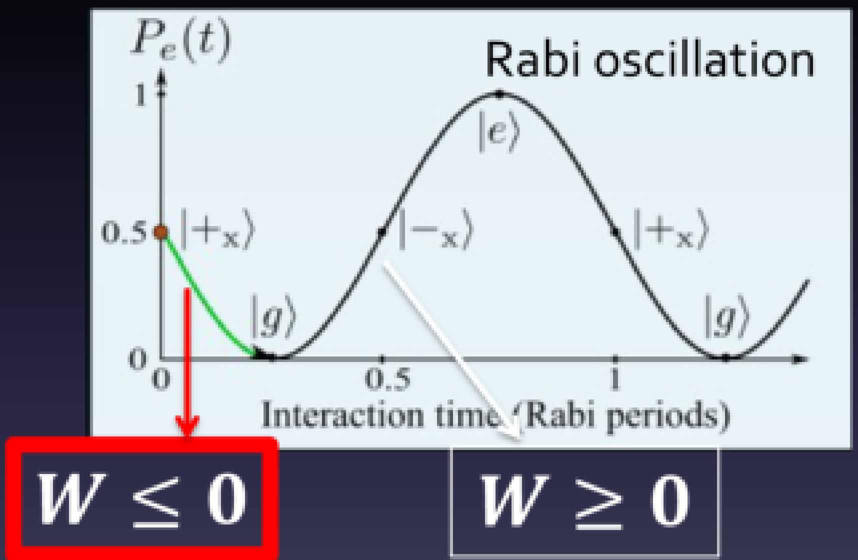
« Coherent control » = another way of preparing coherent superpositions

Basic mechanism of the engine

The qubit exchanges **work** with a resonant driving field



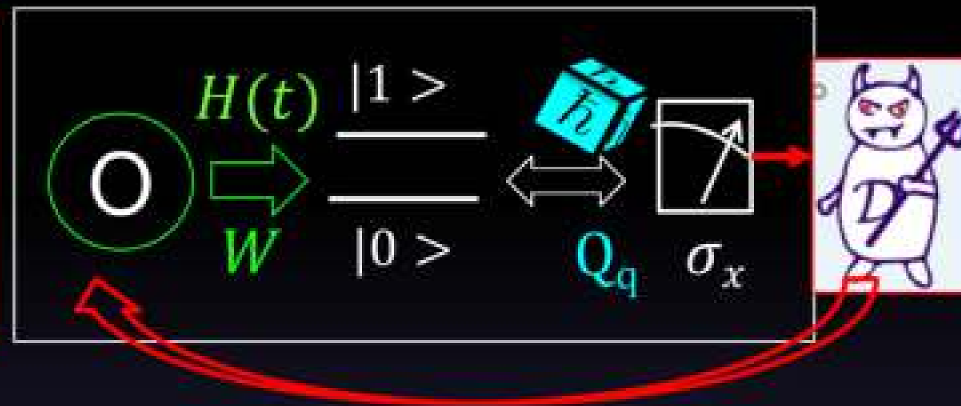




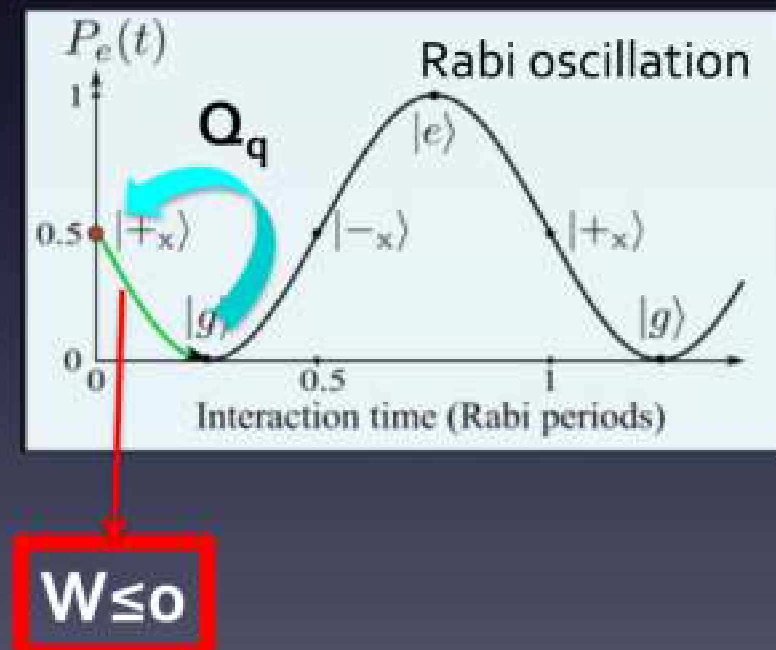
- $|+_x>$ = good for work extraction ☺
- $|-_x>$ = bad for work extraction ☹

Basic mechanism of the engine

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

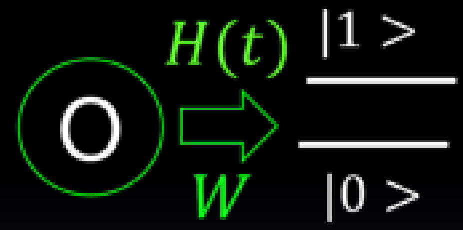


- New quantum Maxwell's demon experiment
- Energy $<Q_q>$ is extracted from the measurement and converted to work $<W>$

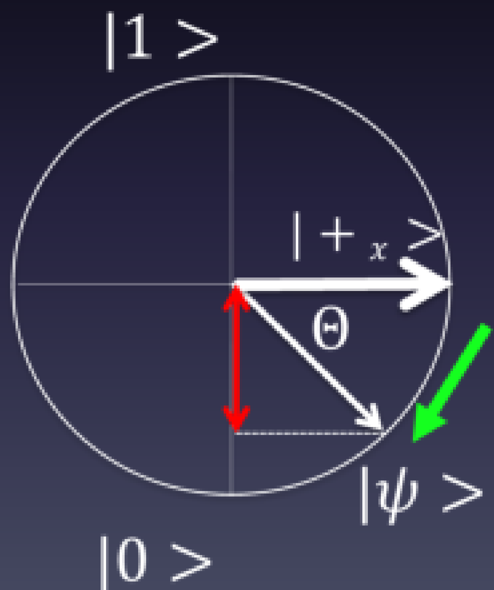


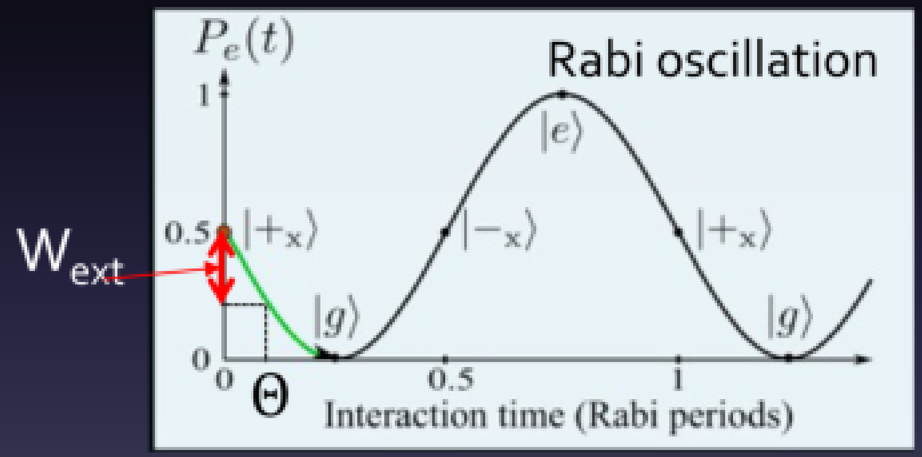
Measurement powered engine (MPE)

0. Initialize in $|+_x>$ and couple to a resonant field



1. Work extraction



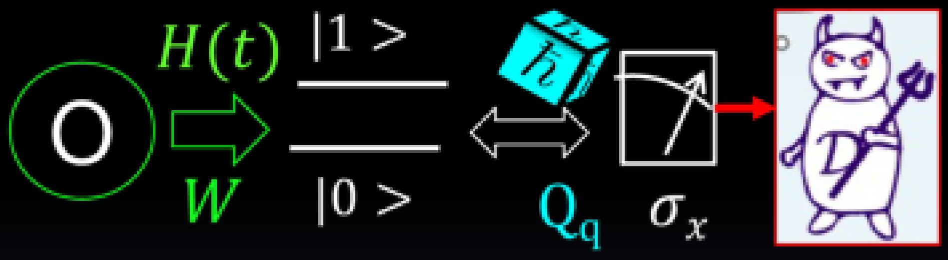


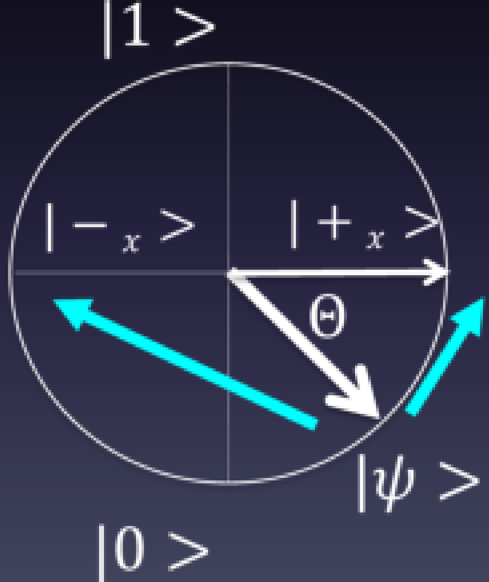
$$\Theta = \Omega t$$

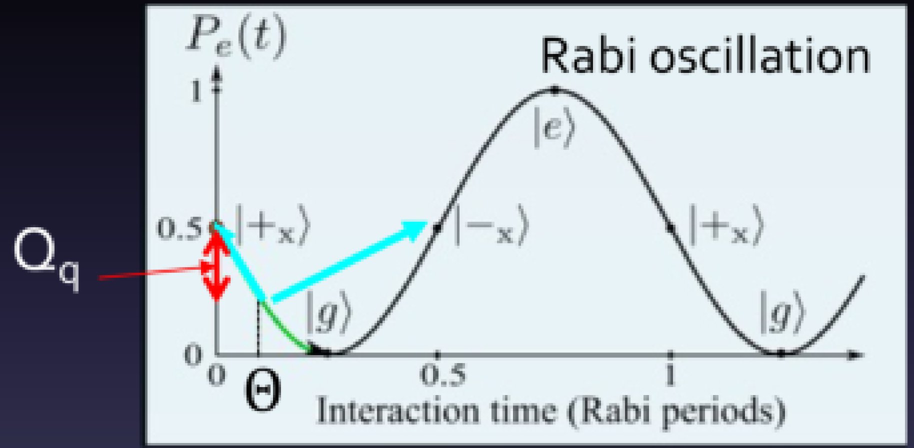
$$W_{ext} = h\nu_0 \sin(\theta)/2$$

Measurement powered engine (MPE)

2. Readout
Quantum heat exchange







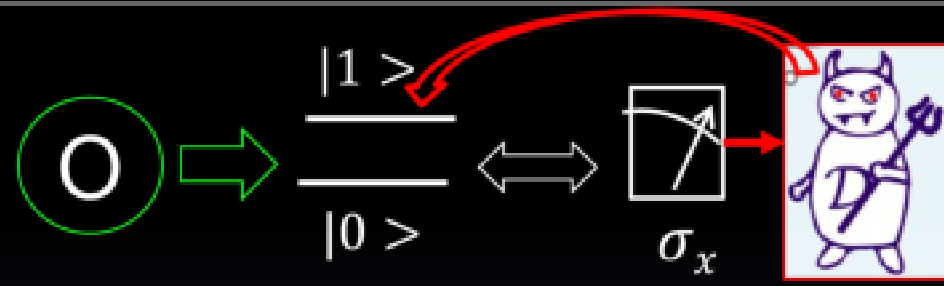
$|\psi> \to |+_x>: P_\theta = \cos^2(\theta)$

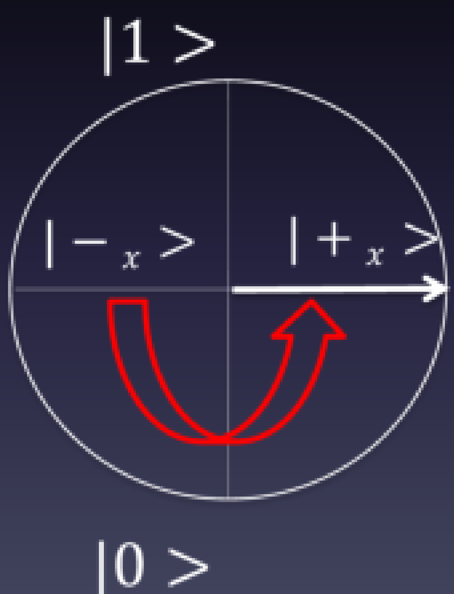
$|\psi> \to |-_x>: 1 - P_\theta = \sin^2(\theta)$

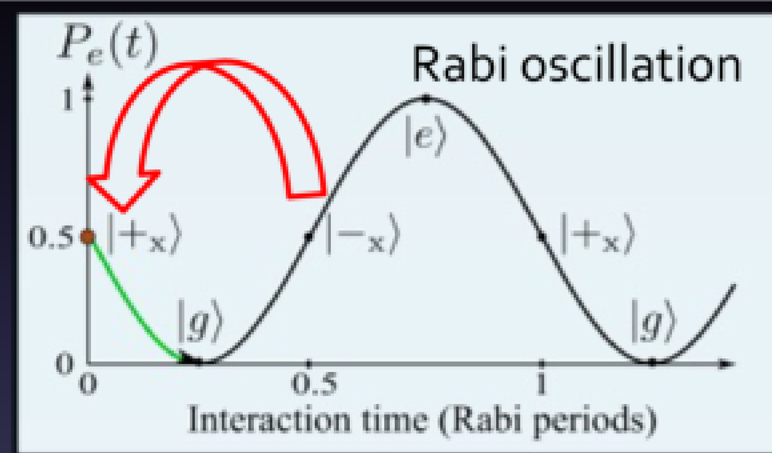
$Q_q = h\nu_0 \sin(\theta)/2$

Measurement powered engine (MPE)

3. Feedback
No energy cost







$$U(+) = U(-) = \frac{h\nu_0}{2}$$

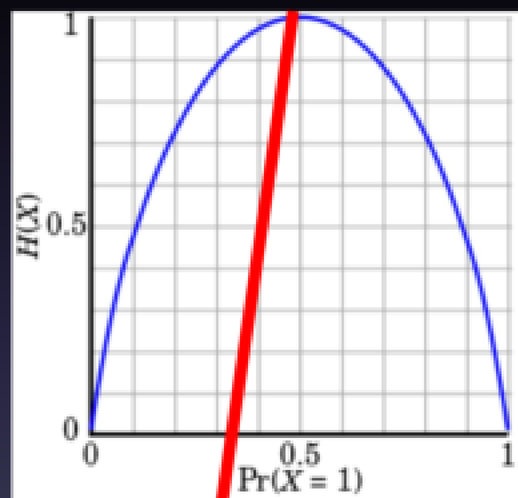
$$W_{fb} = 0$$

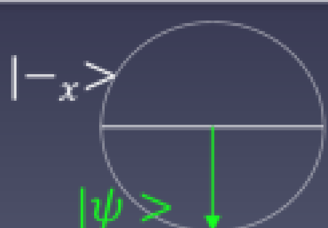
Measurement powered engine (MPE)

4. Memory erasure
Landauer's work
$\boldsymbol{W_{er} = T_D S_D}$

Entropy of the demon's memory $S_D = H[P_\theta]$
H[P] Shannon's entropy

$$H[P] = -P\log(P) - (1-P)\log(1-P) \text{ with } P_\theta = cos^2(\theta)$$





$\theta \sim \pi/2$
$P_\theta = 1/2$
$S_D = 1\ bit$

- Maximal uncertainty on the measurement outcomes
- Maximal entropy

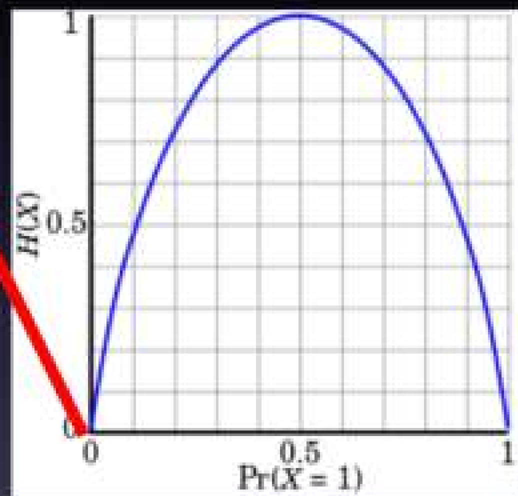
Measurement powered engine (MPE)

4. Memory erasure
Landauer's work
$\boldsymbol{W_{er} = T_D S_D}$

Entropy of the demon's memory $S_D = H[P_\theta]$
H[P] Shannon's entropy

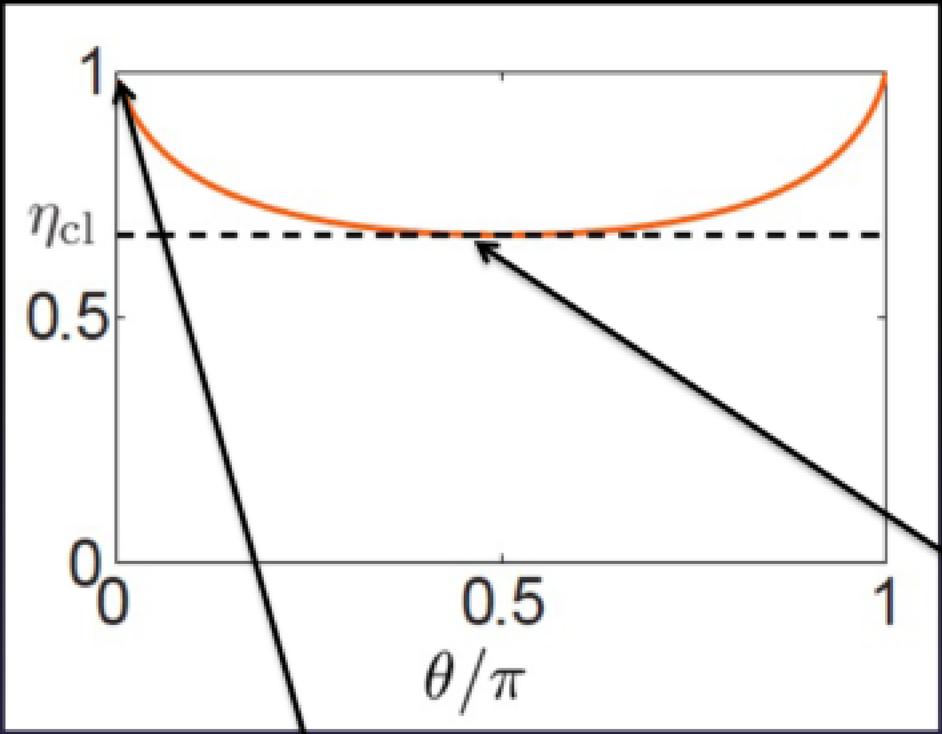
$$H[P] = -P\log(P) - (1-P)\log(1-P) \text{ with } P_\theta = cos^2(\theta)$$

$\theta \sim 0$
$P_\theta = 1$
$S_D = 0$



- Certain result
- Zeno regime

MPE performances: Yield



Engine's yield:

$$\eta(\theta) = 1 - \frac{W_{er}}{Q_q}$$

W_{er} erasure work
Q_q quantum heat

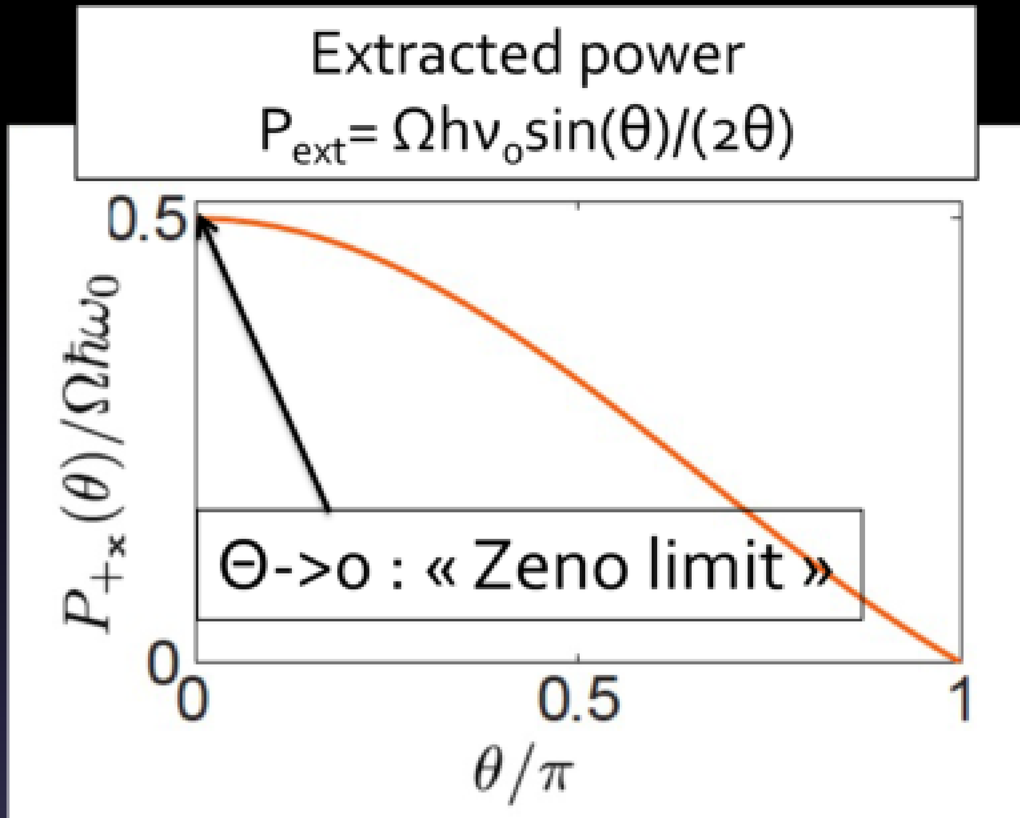
η minimal for $\theta = \frac{\pi}{2}$

$\theta \rightarrow 0$: Zeno limit

- Qubit « frozen » in the $|+_x>$ state
- $W_{er} \approx \theta^2 \ln(\theta) \sim 0$: **Yield η->1**
- **Perfect conversion of the quantum heat into work**

Elouard et al, PRL 118, 260603 (2017)

MPE performances: Extracted power



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

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

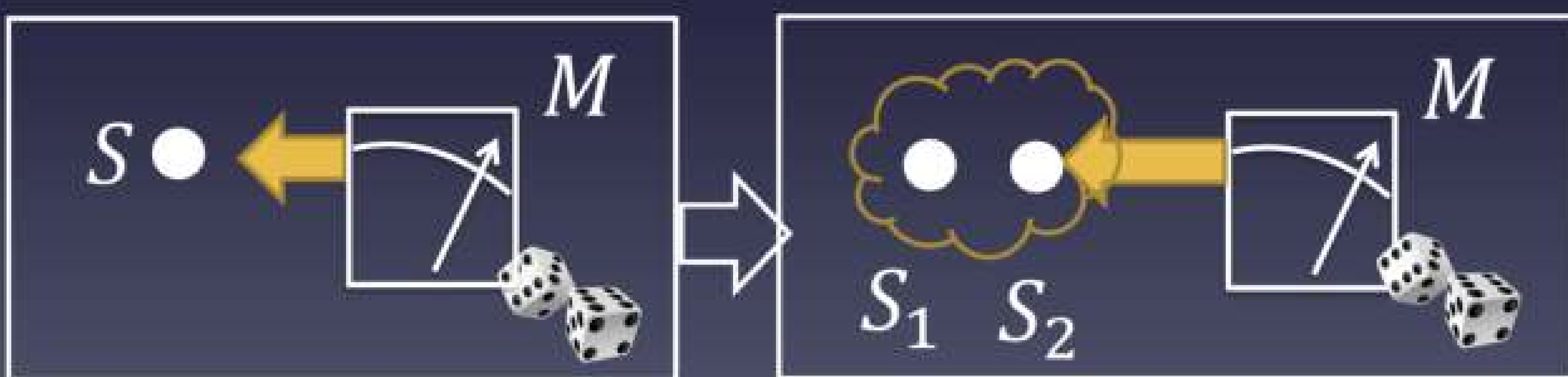
First batch of take home messages

- Build up of a consistent thermodynamic framework, on the sole randomness induced by the measurement postulate
- Irreversibility of quantum nature
- Energy transfers of quantum nature = « quantum heat »

- Build up of measurement-powered engines

⇒ Extension to multi-partite working substance?

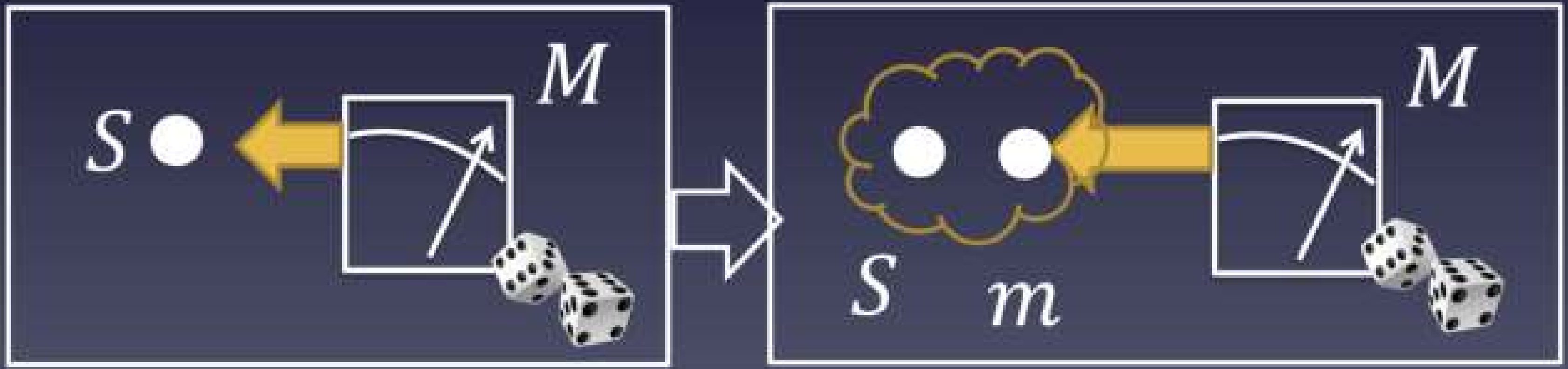
⇒ Role of entanglement?



First batch of take home messages

- Build up of a consistent thermodynamic framework, on the sole randomness induced by the measurement postulate
- Irreversibility of quantum nature
- Energy transfers of quantum nature = « quantum heat »

- But measurement is also related to information extraction = work cost
- Are measurement induced energy transfers heat or work??

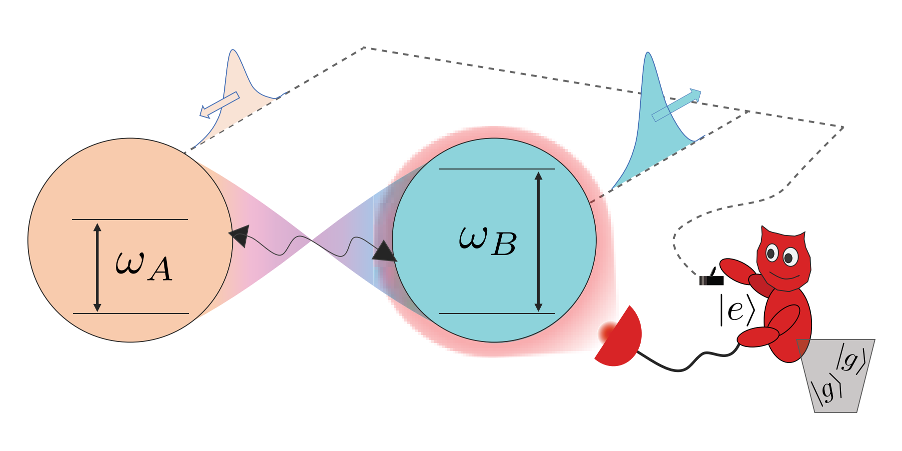


PHYSICAL REVIEW LETTERS **126**, 120605 (2021)

Editors' Suggestion

Two-Qubit Engine Fueled by Entanglement and Local Measurements

Léa Bresque,[1] Patrice A. Camati,[1] Spencer Rogers,[2] Kater Murch,[3] Andrew N. Jordan,[2,4] and Alexia Auffèves[1,*]
[1]*Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*
[2]*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
[3]*Department of Physics, Washington University, St. Louis, Missouri 63130, USA*
[4]*Institute for Quantum Studies, Chapman University, Orange, California 92866, USA*



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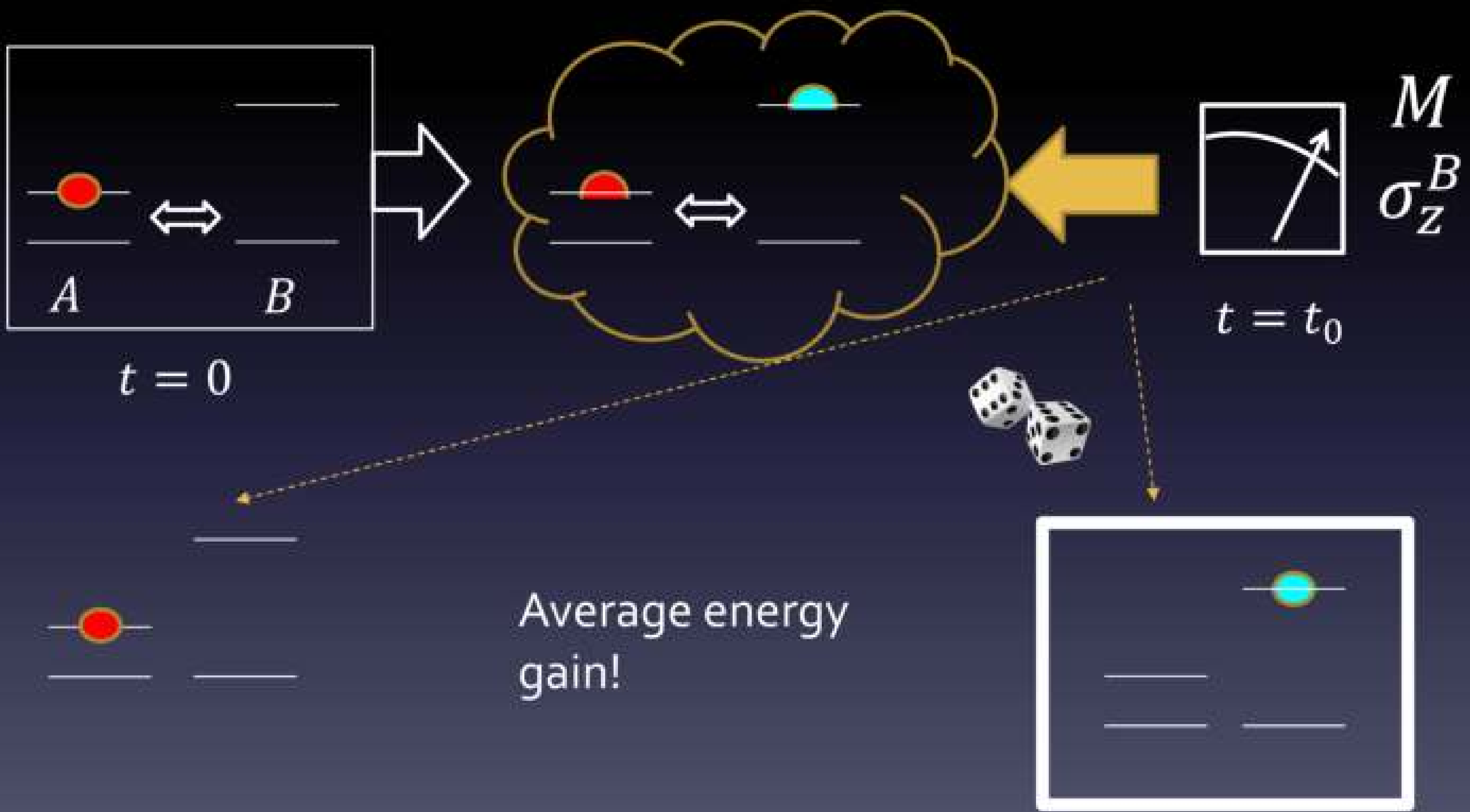
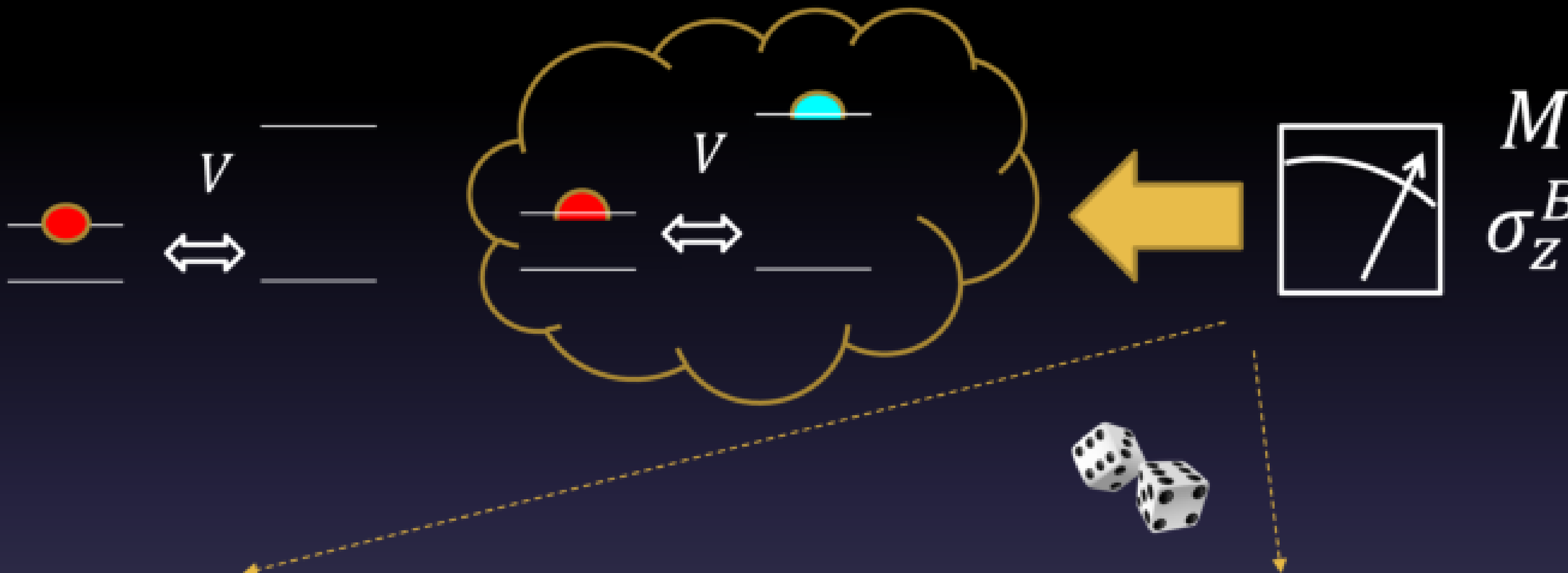
A two-qubit engine powered by entanglement and local measurements

26 April 2021, by Ingrid Fadelli

Extracting energy from quantum measurement, part 2



Extracting energy from quantum measurement, part 2

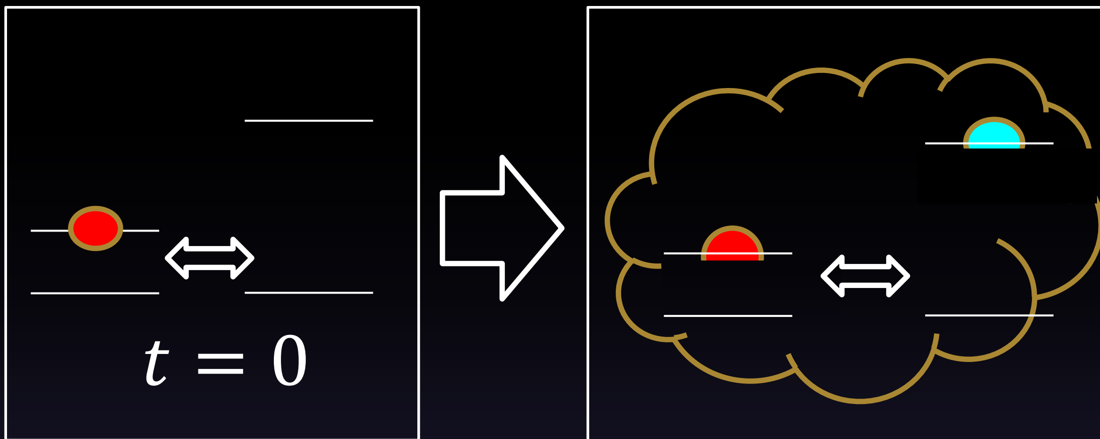


$$V = \frac{\hbar g}{2}(\sigma_A^+ \sigma_B + \sigma_B^+ \sigma_A)$$

$$[H_{tot}, \sigma_z^B] \neq 0$$

- ➢ Input of « quantum heat »

Dynamical insights



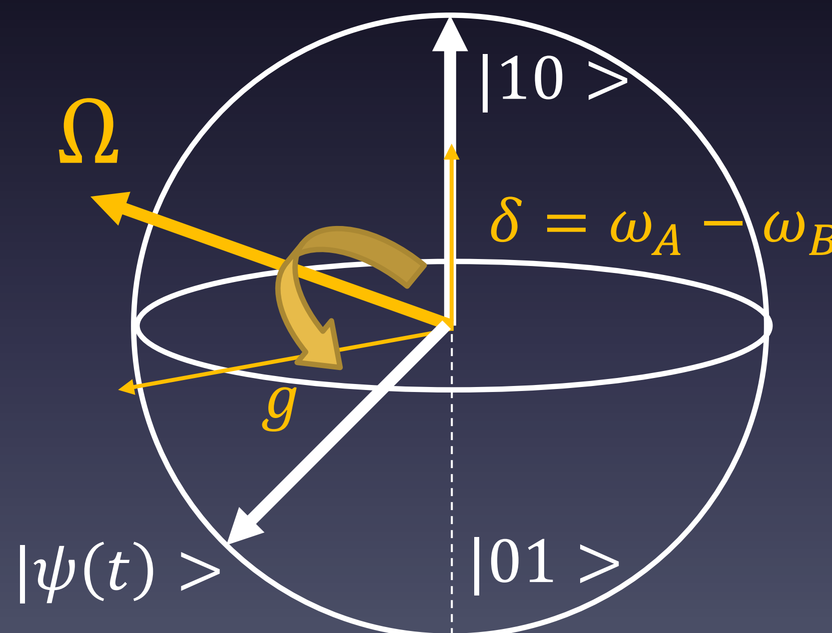
$$H_{2qb} = H_{loc} + V$$

$$H_{2qb} = \frac{\hbar\omega_A}{2}\sigma_z^A + \frac{\hbar\omega_B}{2}\sigma_z^B$$

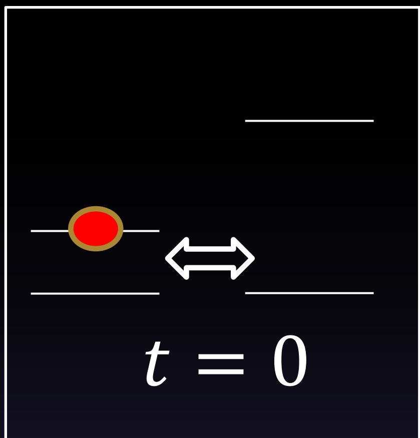
$$V = \frac{\hbar g}{2}(\sigma_A^+\sigma_B + \sigma_B^+\sigma_A)$$

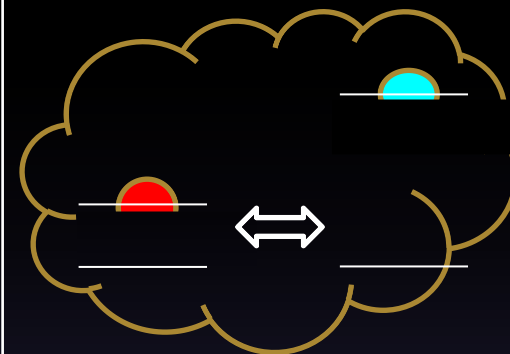
$$|\psi(0)> = |10>$$

$$|\psi(t)> = \alpha(t)|10> + \beta(t)|01>$$



Dynamical insights





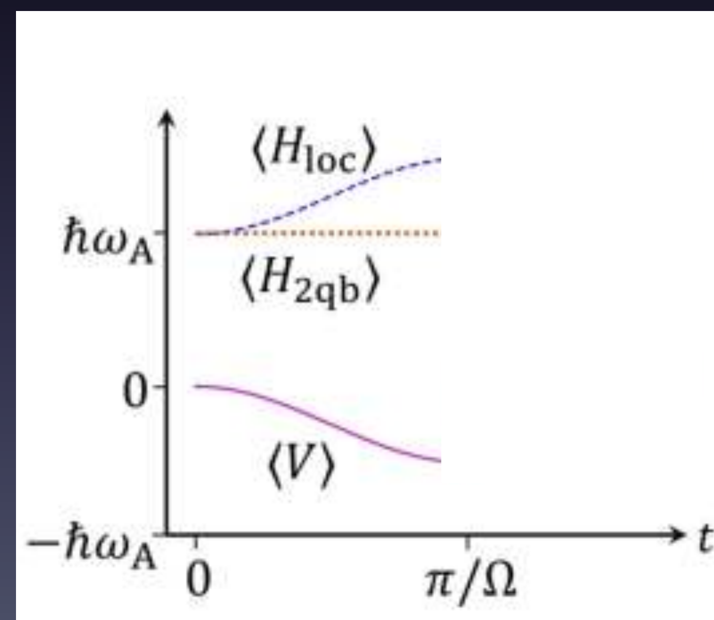
$$H_{2qb} = H_{loc} + V$$

$$H_{loc} = \frac{\hbar\omega_A}{2}\sigma_z^A + \frac{\hbar\omega_B}{2}\sigma_z^B$$

$$V = \frac{\hbar g}{2}(\sigma_A^+\sigma_B + \sigma_B^+\sigma_A)$$

$< H_{2qb} > = \hbar\omega_A$ Energy conservation
$N_A + N_B = 1$ Excitation conservation

$< H_{loc} > = \hbar\delta N_A(t) + \hbar\omega_B$ oscillates
=> $< V >$ oscillates
✓ $< V >$ « binding energy »
✓ **$< V >$ minimal for $t_0 = \pi/\Omega$**



Dynamical insights

$|\psi(t)> = \alpha(t)|10> + \beta(t)|01>$

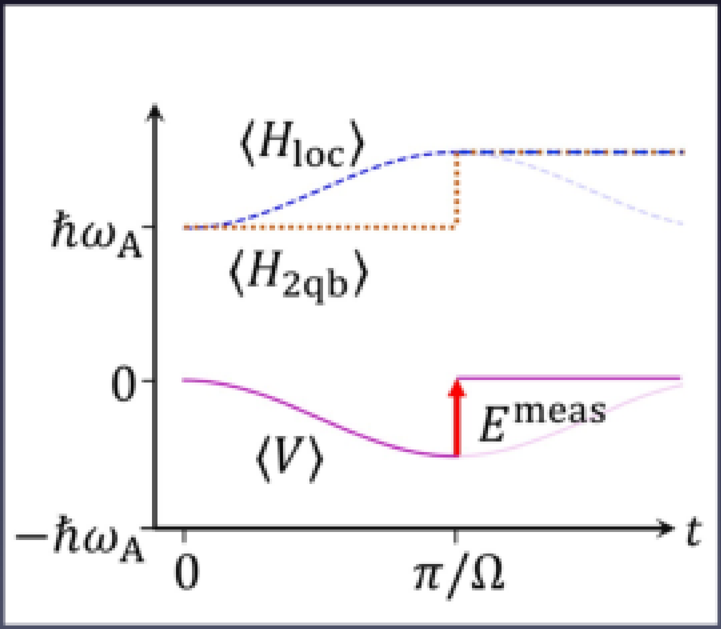
$$V = \frac{\hbar g}{2}(\sigma_A^+ \sigma_B + \sigma_B^+ \sigma_A)$$

$$< V(t) > = \hbar g \, \mathrm{Re}[\alpha \beta^*]$$

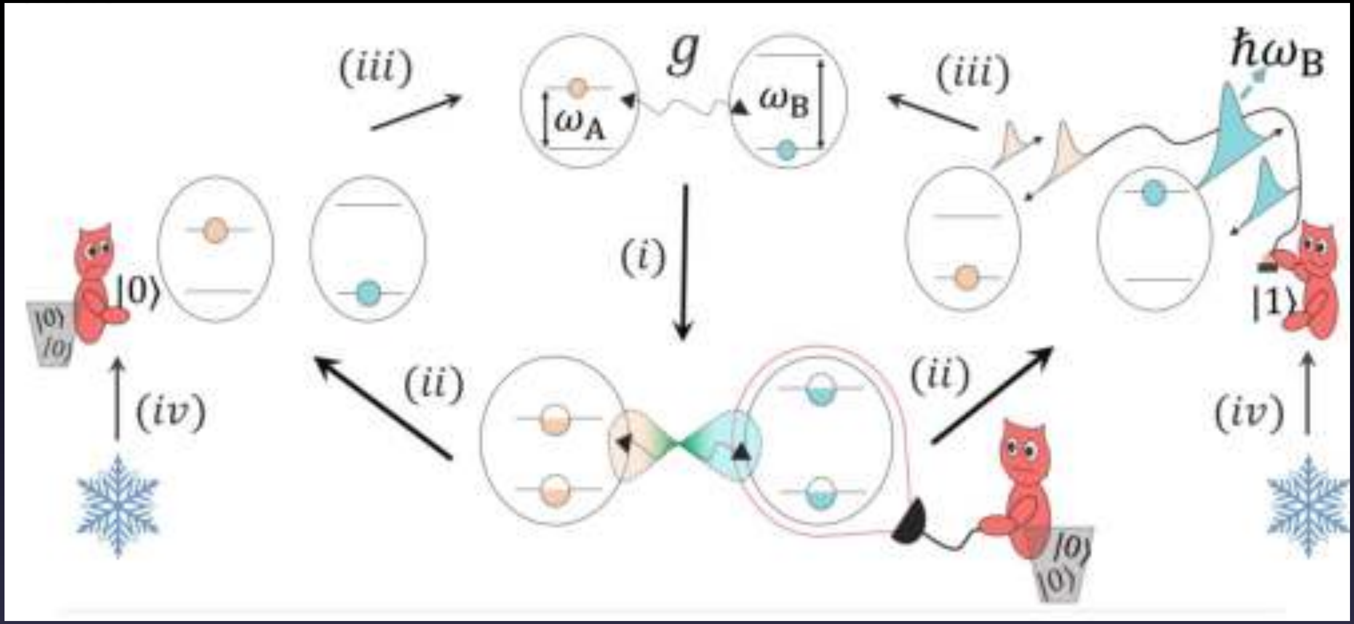
Projective measurement =>

Coherence erasure => Energy gain

$E^{\mathrm{meas}} = -< V(t_0) >$



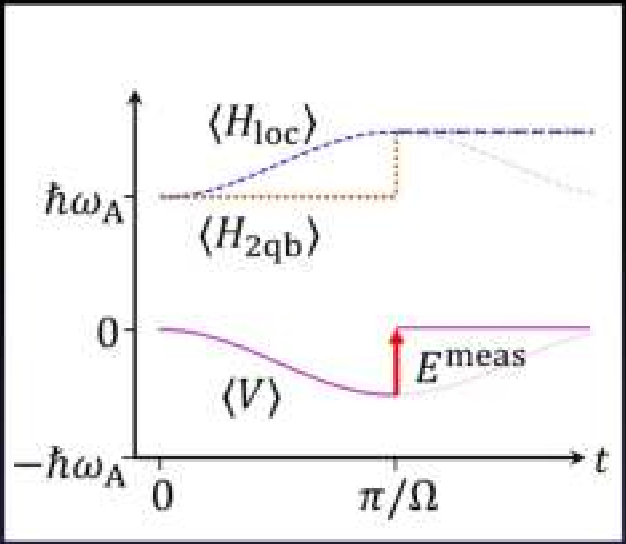
Two-qubit engine powered with entanglement and local measurements

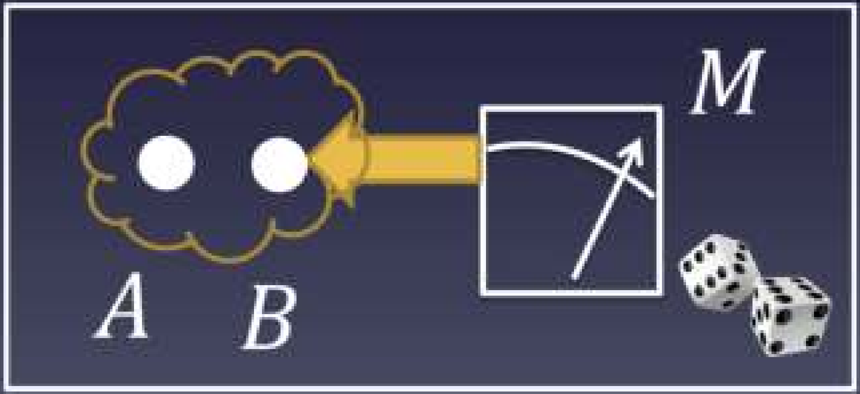


i) Entangling operation
ii) Measurement
iii) Feedback and work extraction
iv) Erasure

Origin of the measurement fuel

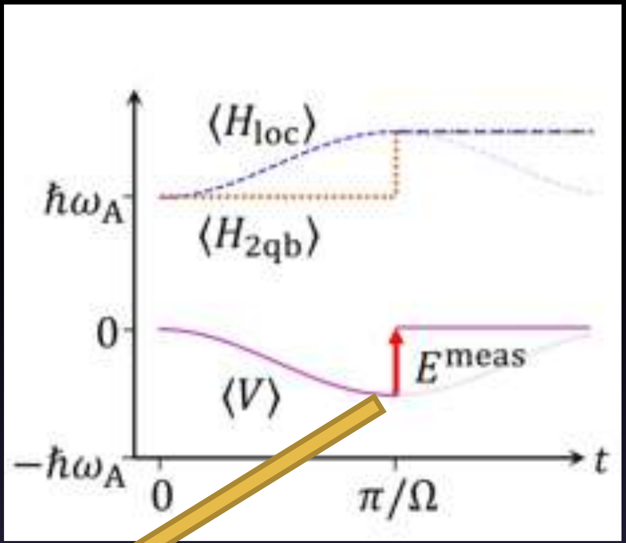
- ✓ So far, measurement fuel treated as heat = energetic fluctuations stemming from the instantaneous projective measurement





Origin of the measurement fuel

- <u>Going beyond:</u> model the measuring channel using Von Neumann two-step approach
- Who pays for the fuel?
- Is it work or heat?



Quantum meter

- Focus on the pre-measurement

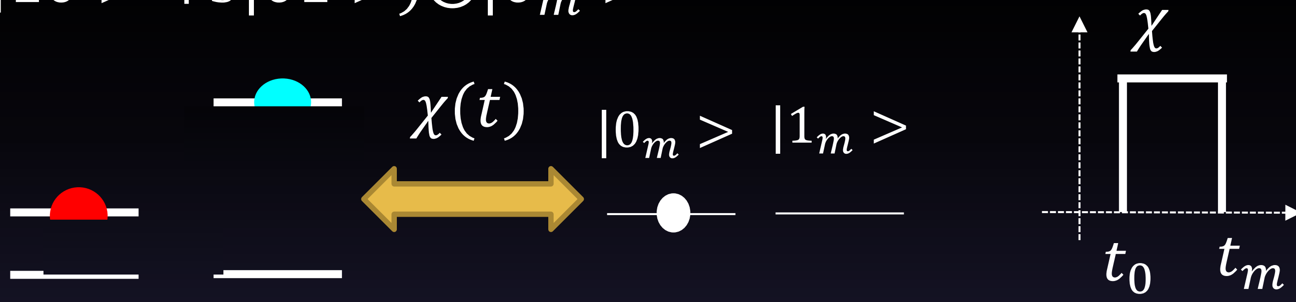
$V_m(t) = \hbar\chi(t)\sigma_B^{+}\sigma_B \otimes \sigma_x^{m}$

$t\epsilon[t_0 = \pi/\Omega, t_m]$

Modeling the pre-measurement

$|\Psi(t_0)\rangle = (c|10\rangle + s|01\rangle) \otimes |0_m\rangle$

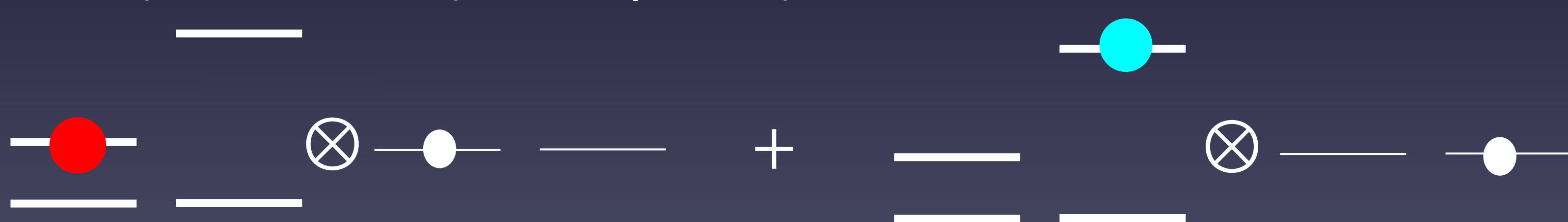
A and B uncoupled



Ideal measurement

$|\Psi^0(t_m)\rangle = c|100_m\rangle + s|011_m\rangle$

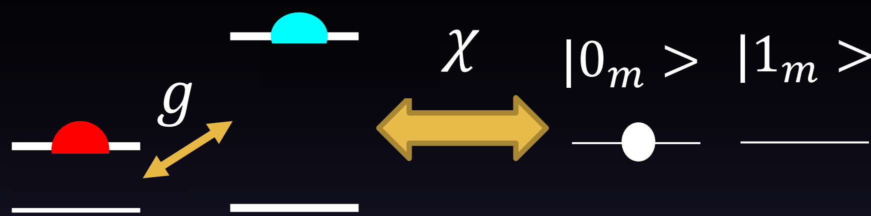
$t_m = t_0 + \pi/\chi$

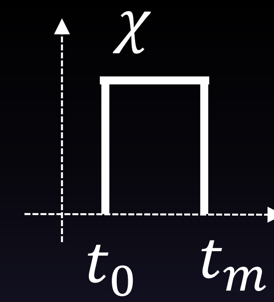


Modeling the pre-measurement

A and B coupled

$$|\Psi(t_0) = (c|10> + s|01>) \otimes |0_m>$$





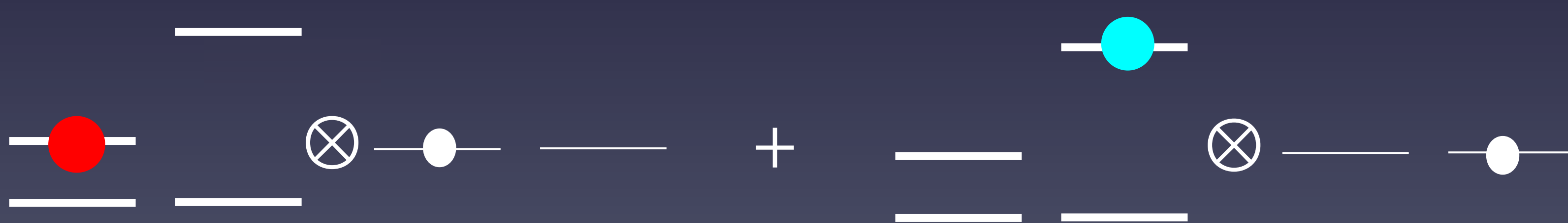
$\varepsilon = g/\chi \ll 1$

Perturbation parameter

Short measurement compared to Rabi period

$$|\Psi(t)> = |\Psi^{(0)}(t)> + |\delta\Psi(t)>$$

$$t_m = t_0 + \pi/\chi$$

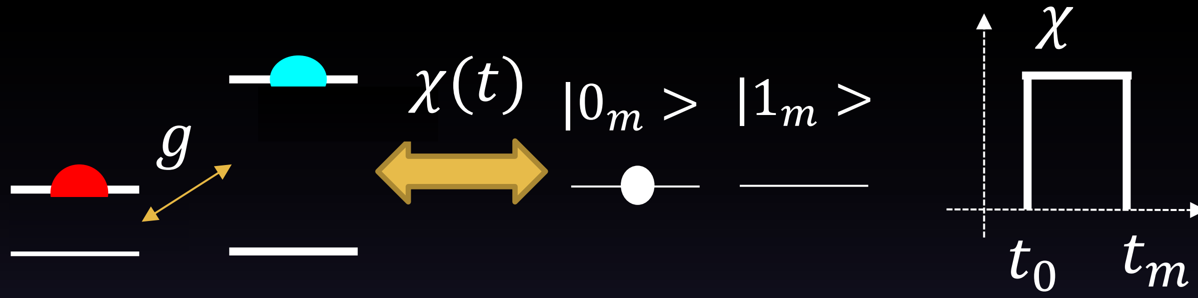


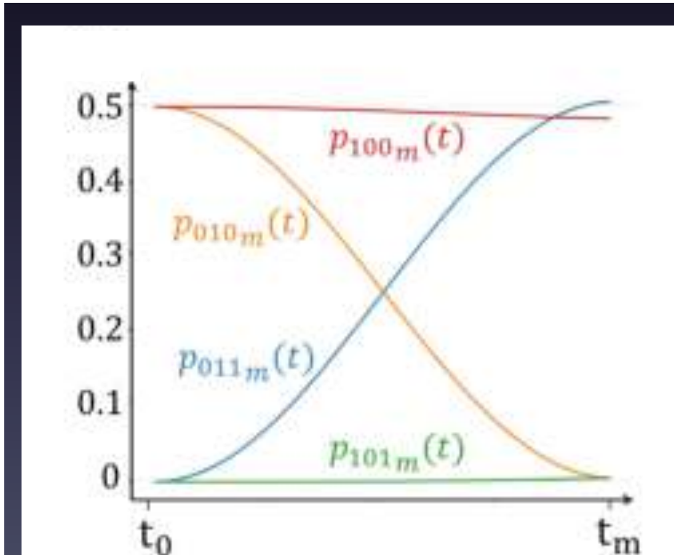
$+ \ldots +$

Qubits-meter evolution

$\varepsilon = g/\chi \ll 1$

perturbation parameter





$$|\Psi(t_0)) = (c|10> + s|01>) \otimes |0_m>$$

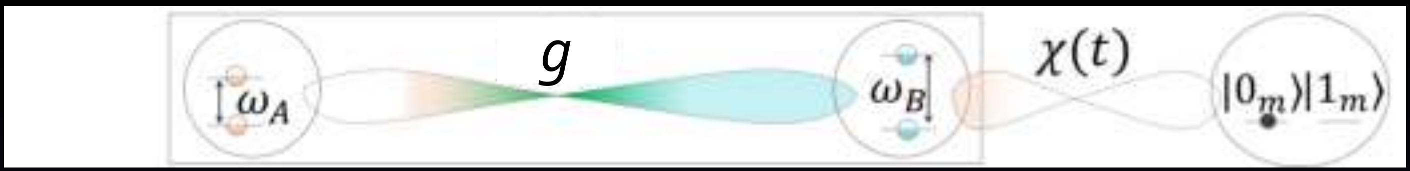
⇩

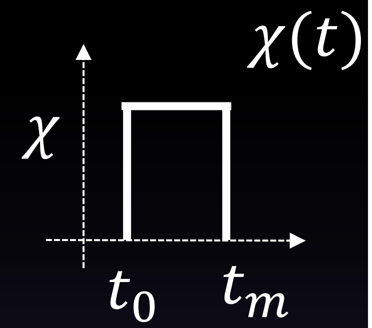
$$|\Psi(t)> = |\Psi^{(0)}(t)> + |\delta\Psi(t)>$$

$$|\Psi^{(0)}(t_m) = c|100_m> + s|011_m>$$

$|\Psi(t)>$ = a superposition of $|100_m>$, $|101_m>$, $|010_m>$, $|011_m>$

Energetic analyzis





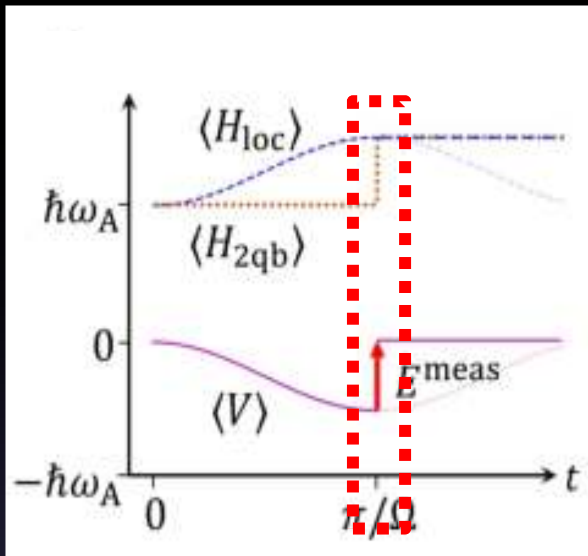
$$H_{tot} = H_{loc} + V + V_m, H_{2qb} = H_{loc} + V$$

$$V = \frac{\hbar g}{2}(\sigma_A^+\sigma_B + \sigma_B^+\sigma_A), V_m(t) = \hbar\chi(t)\sigma_B^+\sigma_B \otimes \sigma_x^m$$

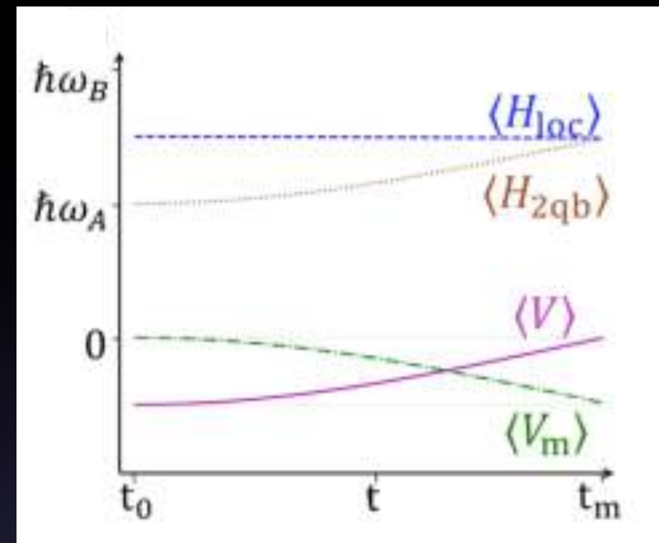
<u>Thermodynamic system:</u> Qubit A, Qubit B, quantum meter M

- $t \in]t_0, t_m[$: ABM isolated system => $< H_{tot}(t) >$ constant
- $t = t_0, t_m$: An agent switches on and off the measurement channel $\Rightarrow$ Work input $< \Delta H_{tot}(t) > = W(t) =< \Delta V_m(t) >$
- $t = t_0$: $< \sigma_x^m > = 0 \Rightarrow W(t_0) = 0$

Energetic flows ($t \in]t_0, t_m[$)



Zoom!



$< H_{loc} >$ constant during the measurement ($\chi \gg g$)

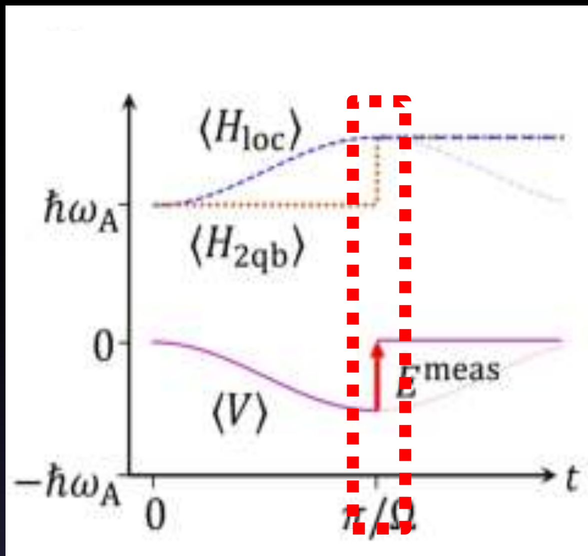
$< V(t) > = < \Psi^{(0)}(t)|V|\Psi^{(0)}(t)>$ at first order in ε

$|\Psi^0(t_m) >= c|100_m > +s|011_m > \Rightarrow < V(t_m) > = 0$

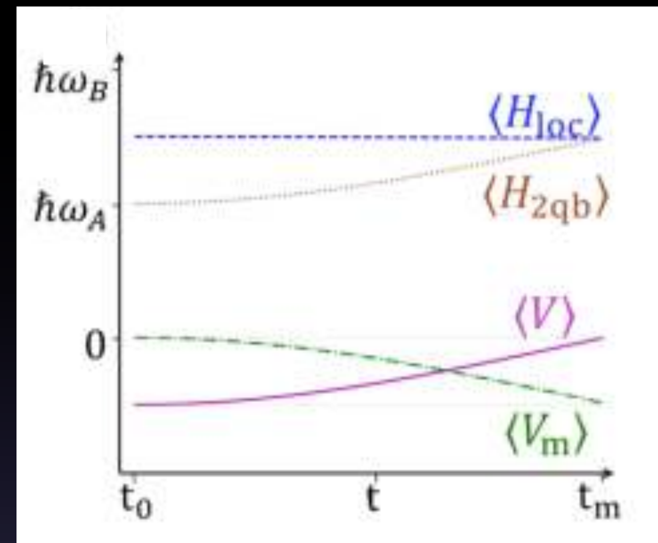
$\Rightarrow < \Delta V > = -V(t_0) = E^{meas} =< \Delta H_{2qb} >$

✓ **One recovers the expected behavior for the qubits system (increase of energy and entropy)**

Energetic flows ($t \in]t_0, t_m[$)



Zoom!



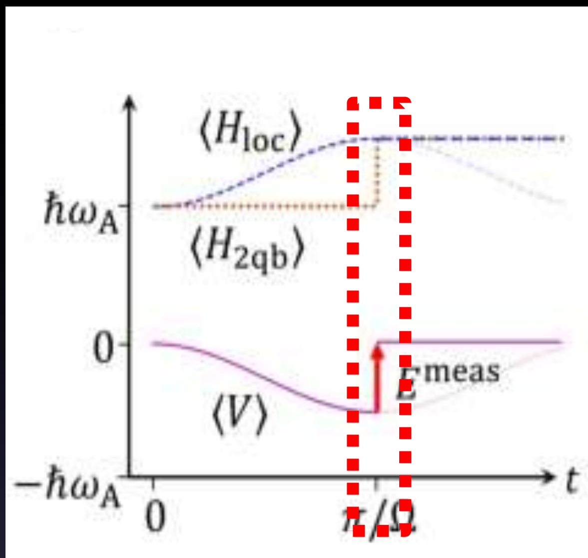
$< H_{tot} >$ constant during the measurement (isolated system)

$< V_m(t) > + < V(t) >$ constant

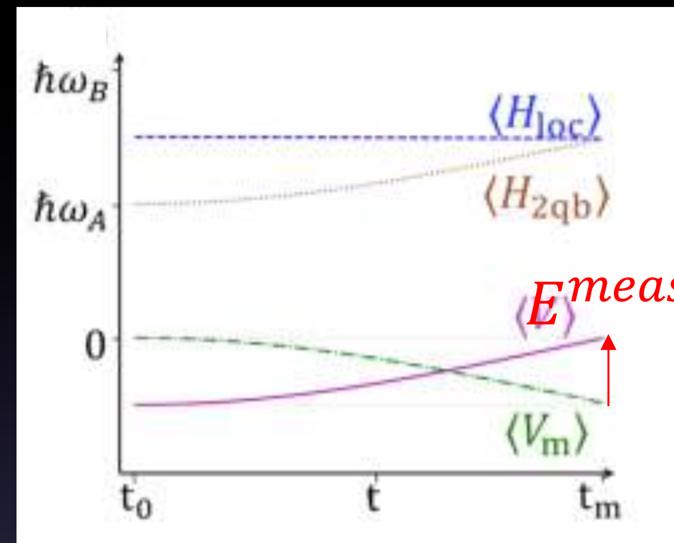
$\Rightarrow < \Delta V_m > = - < \Delta V > = -E^{meas}$

✓ **The binding energy initially localized between the qubits is now localized between the qubits and the meter**

Energetic flows ($t = t_m$)



Zoom!



While the measurement channel is switched off:

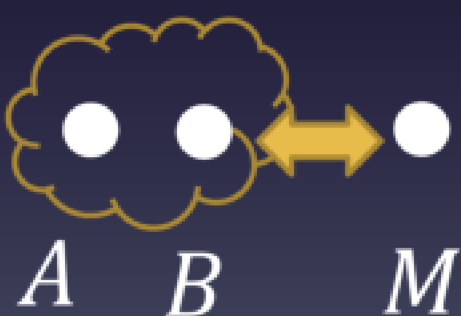
$< H_{loc} >, < V >, < H_{2qb} >$ remain constant

$< \Delta V_m > = E^{meas}$ **= Work provided by the agent to the** $\boldsymbol{ABM}$ **joint system**

Work or heat?

Projective measurement on AB

- ✓ Increase of energy and entropy
- ✓ Irreversible transformation
- ✓ « Quantum heat »

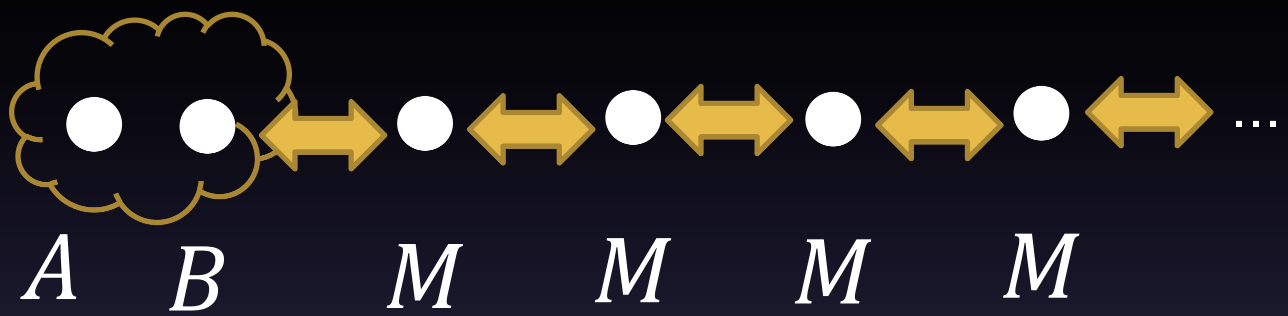


Entanglement of AB with meter M

- ✓ Reversible, entropy preserving energy input on ABM => « Work »
- ✓ Irreversible energy input on AB => « Heat »

Is quantum heat fundamental?

It depends on your favourite interpretation…



- ✓ Measurement = creation of massive entanglement by unitary transformations
- ✓ Reversible, entropy preserving
- ✓ Measurement energy= Work
- ✓ *Typical interpretation: Everett*

Is quantum heat fundamental?

It depends on your favourite interpretation…

Von Neumann's legacy

- ✓ Always a classical measurement that ends the channel
- ✓ Irreversible, not entropy preserving
- ✓ **Measurement energy is fundamentally heat**

Outline


- Thermodynamics, from classical to quantum
- Thermodynamics of quantum measurement
- A measurement-powered quantum engine
- **Application to quantum information technologies**

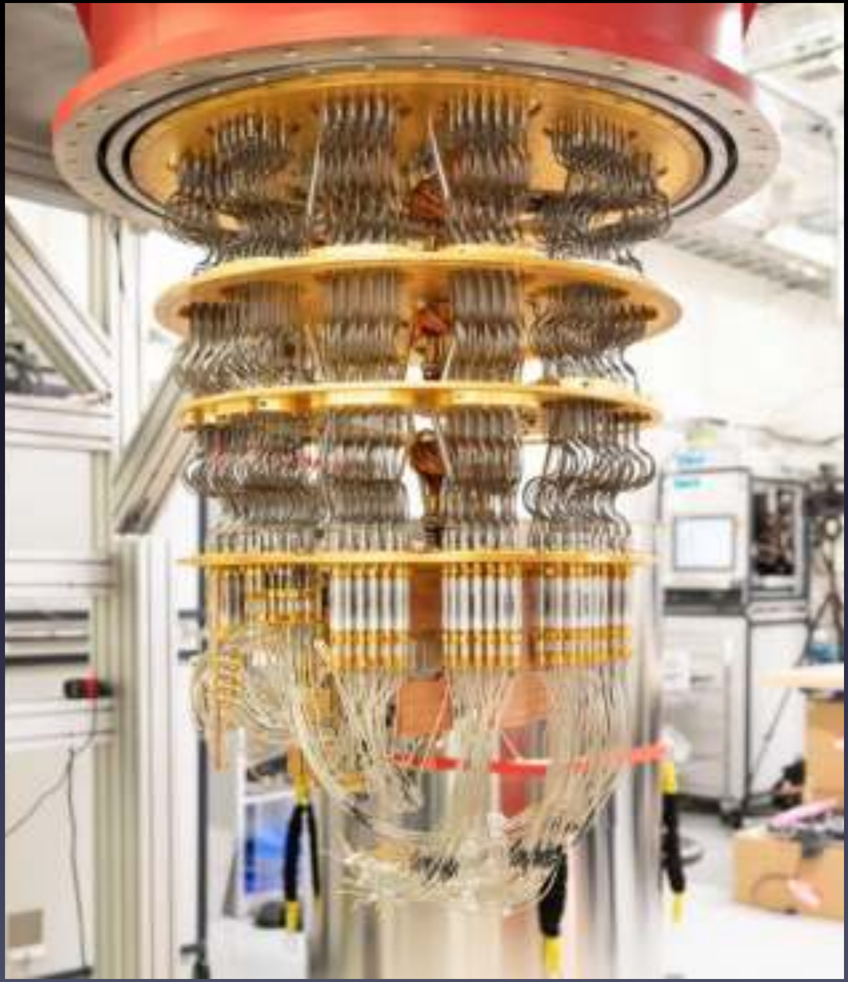
Is there a quantum energetic advantage?

- Google Sycamore: 25kW
- IBM Summit: 10MW

=> Scaling laws for universal quantum computer?

Fundamental arguments for energetic quantum advantage

- Quantum logic offers gain in complexity
- Quantum logic is reversible



Ideal situation

Algorithm programmation

00001101100…

$\hat{U}$

$|0_n >$

Register preparation,
n physical qubits

$|\psi_n >$

11010…

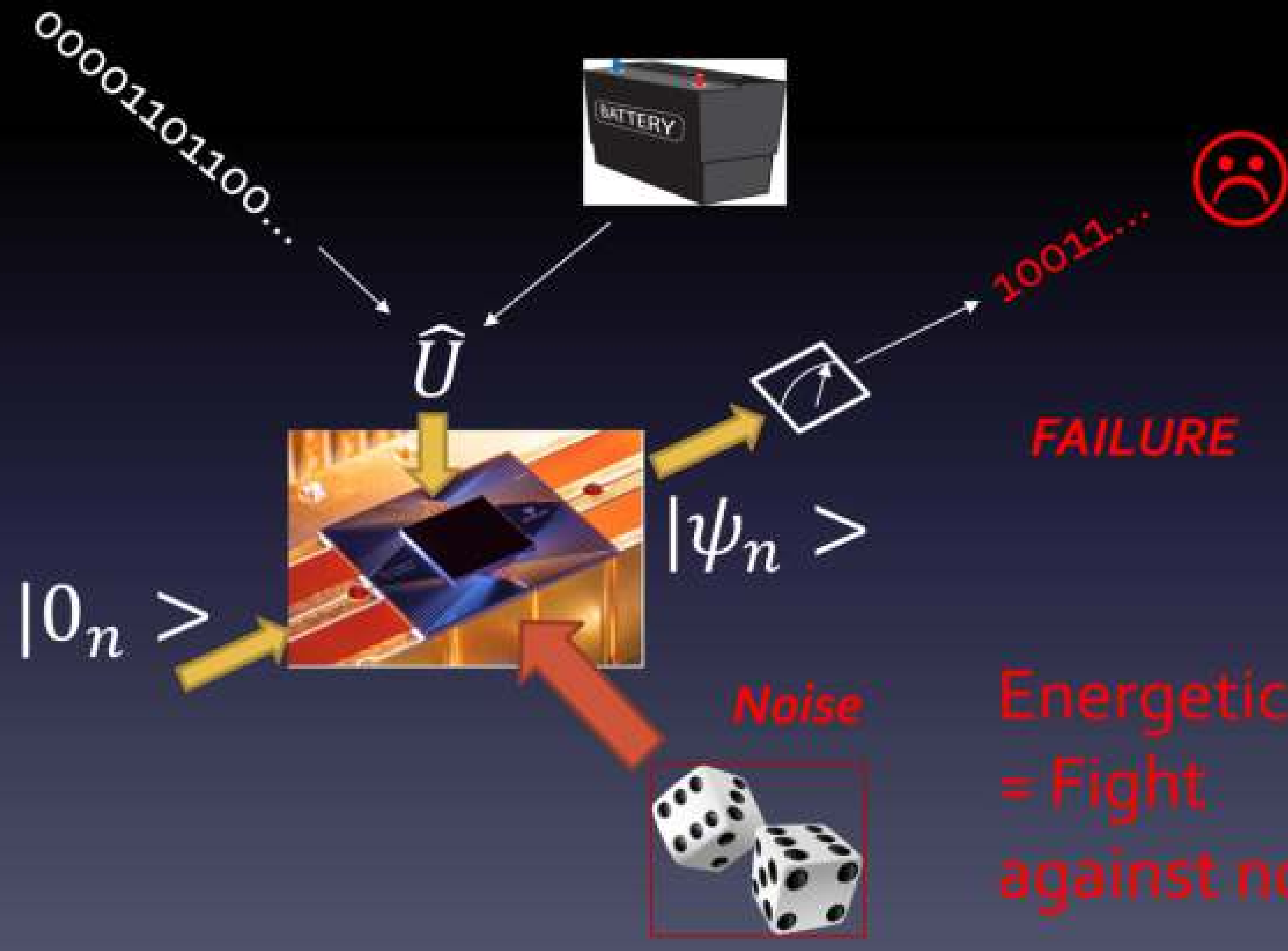
Readout

SUCCESS

☺

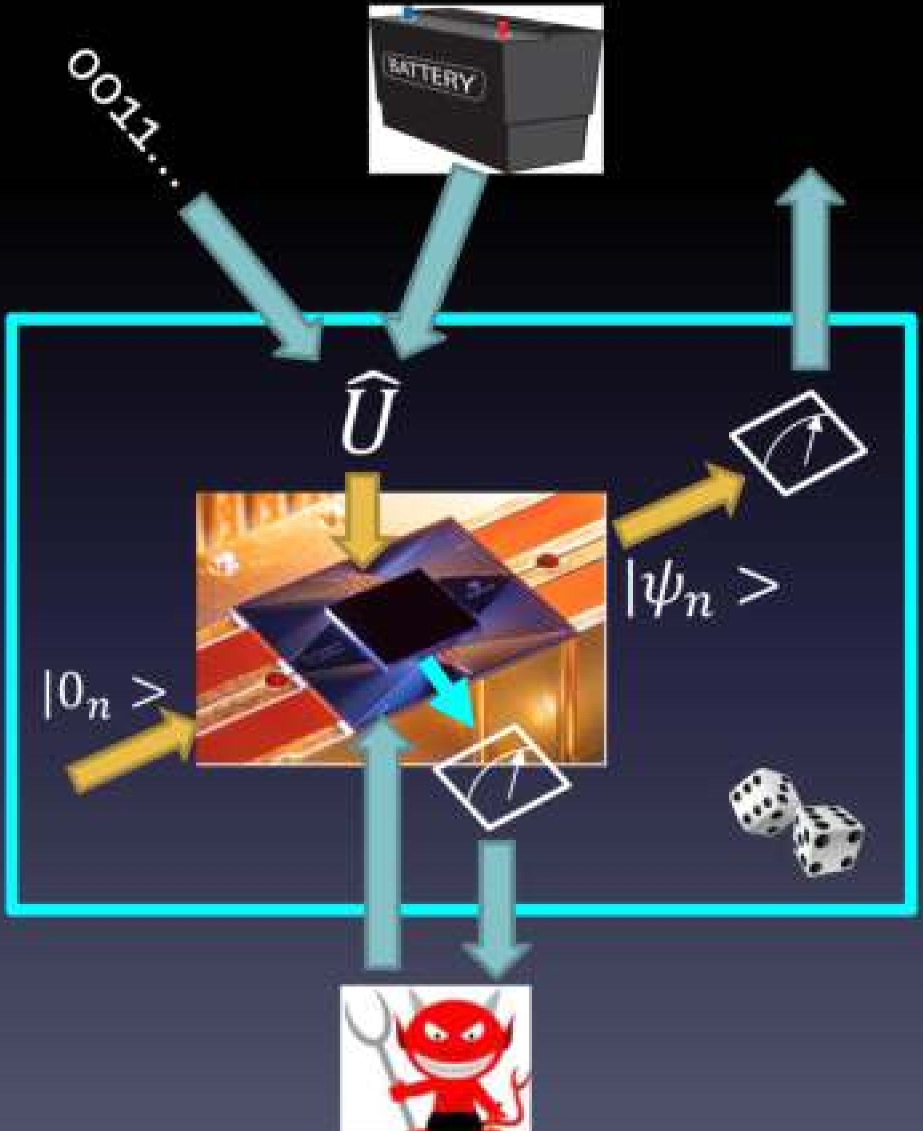
No noise =>
Full energetic quantum advantage

Real situation



Energetic bill = Fight against noise

Fighting the noise in 3 steps



1)Isolate your processor, *but communicate with the outside world!*

2)Compute faster than the noise rate, *but don't burn your processor!*

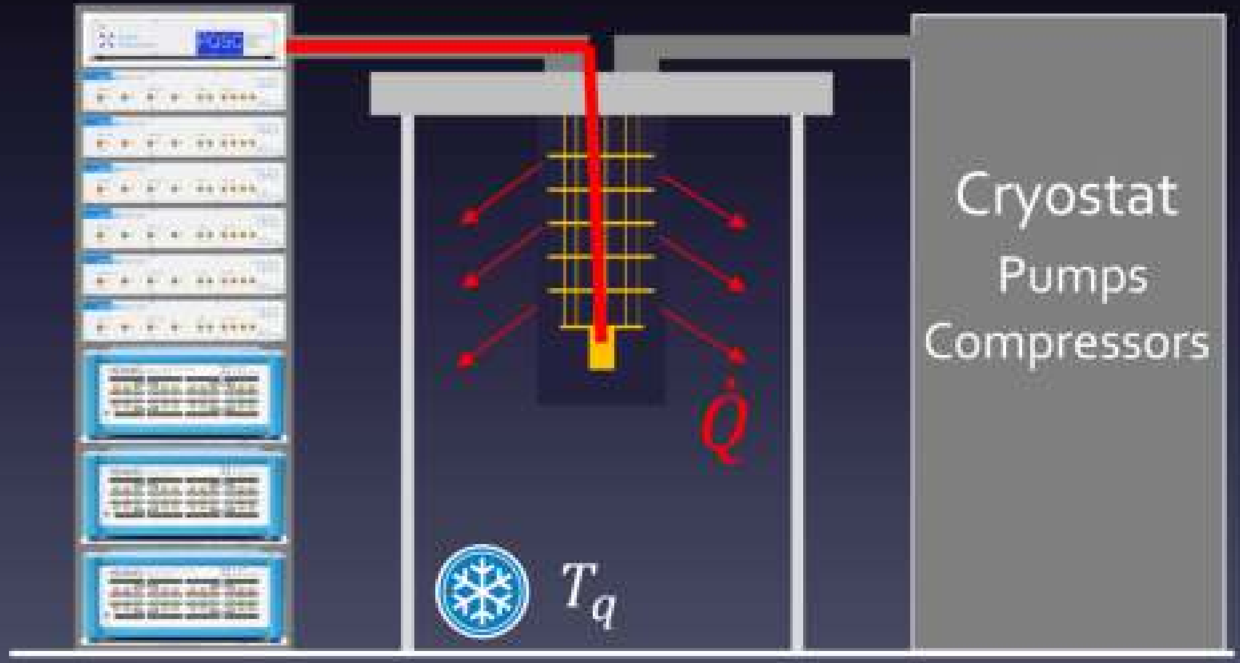
3)Correct errors => *Add physical qubits, but don't add noise!*

Want less noise?
Pay more!

Example: superconducting qubits

Cryogenic cost: $P_C = \epsilon \dot{Q} \left(\frac{T}{T_q}\right)$, ϵ>1

- Lower ϵ the cryogenic yield
- Increase T_q the qubit operating temperature
- Lower $\dot{Q}$ the heat dissipation rate



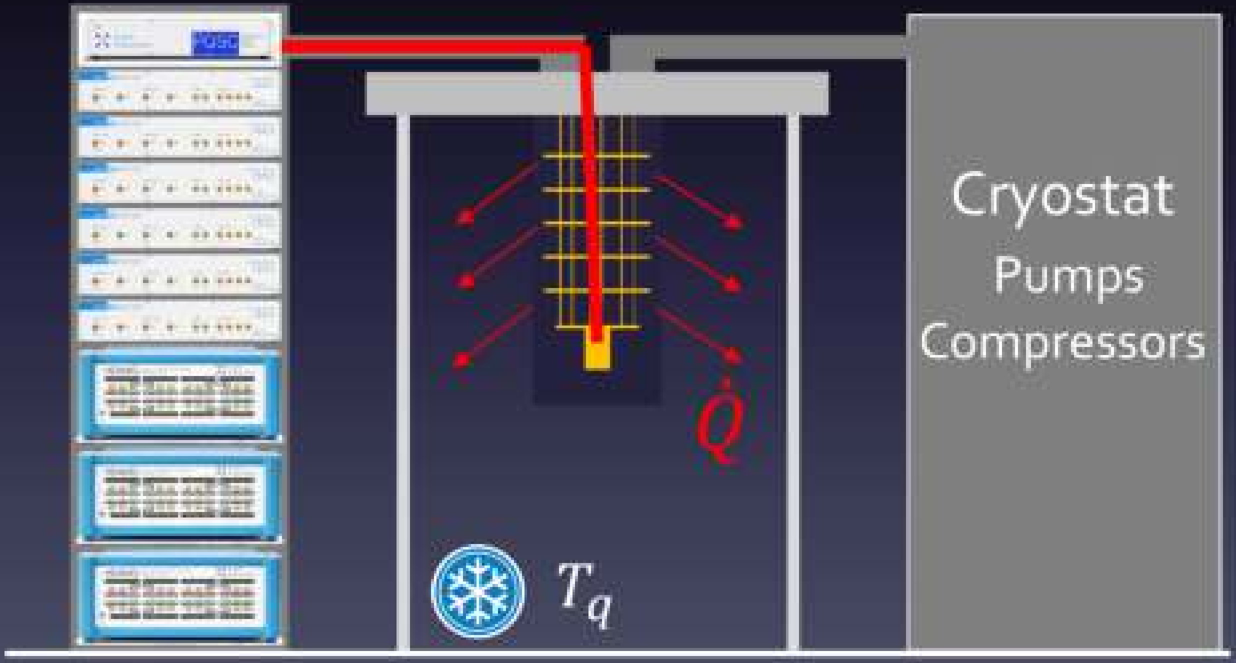
Example: superconducting qubits

Cryogenic cost: $P_C = \epsilon\dot{Q}\left(\frac{T}{T_q}\right)$

Today: μ-wave generation and control electronics at room temperature
$T = 300K, T_q = 1mK$

Macroscopic heat dissipation $\dot{Q}$
- Attenuators
- Conduction losses

Typically 1mW/cable



Towards fully autonomous scenarios

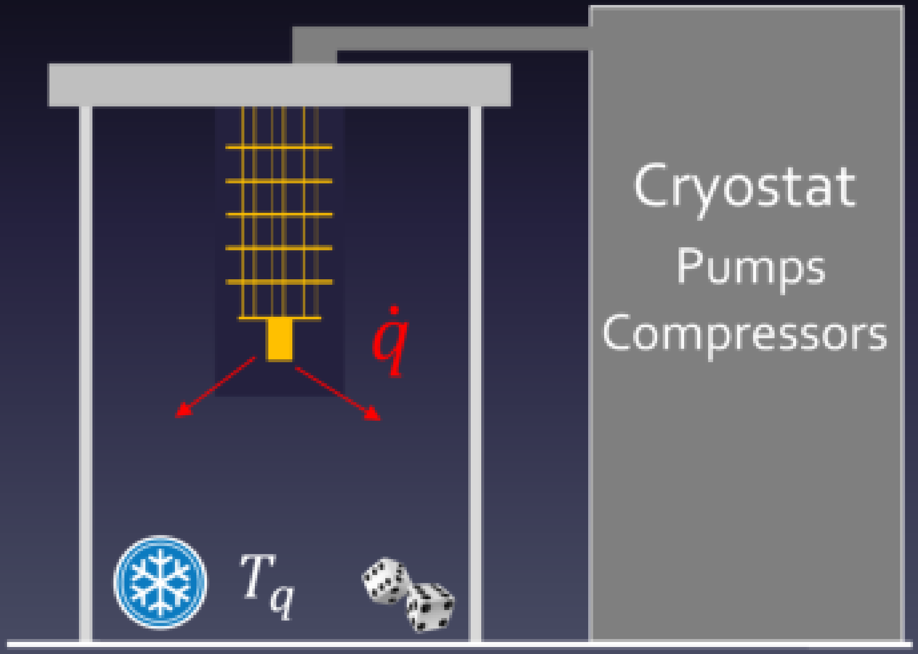
Tomorrow:
- ➢ on-chip μ-wave generation, readout electronics, error correction

Cryo-electronics: $\dot{q} \approx 1mW$/active gate
Scales like the number of physical qubits ☹

$$P_C = \epsilon \dot{q} \left(\frac{T}{T_q}\right)$$

⇒ Need to reduce the footprint of **classical control**
⇒ Reversible computing

⇒ Fundamental cost will scale like the remnant noise rate



Interdisciplinary challenges for energetic scalability solutions

Hardware
- increase the operating temperature
- lower the noise level
- ➢ new qubits engineering

Information processing
- adiabatic/reversible computing (« beyond Landauer » paradigm)
- autonomous scenarios

Architecture
- code connectivity
- qubits addressing

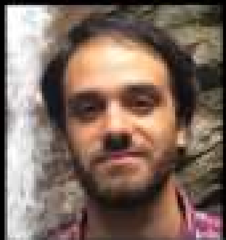
Cryogeny
- improve cooling efficiency
- lower conduction losses

Fundamental physics
- energetic lower bounds (computing, cooling) for arbitrary quantum noise

Going further

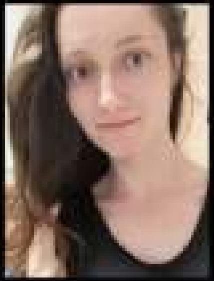
- A.Auffèves, *A short story of classical and quantum thermodynamics*, arXiv 2102.00920, to appear in « Quantum Information Machines; Lecture Notes of the Les Houches Summer School 2019 », eds. M. Devoret, B. Huard, and I. Pop
- M.Fellous-Asiani, J.H. Chai, R. Whitney, A. Auffèves, H.K. Ng, *Limitations in quantum computing from resource constraints*, arXiv 2107.01966
- A. Auffèves, *Optimiser la consommation énergétique des calculateurs quantiques – Un défi interdisciplinaire*, to appear in Reflets de la Physique
- M.Fellous-Asiani, *et al*, *Energetic scalability of a « full stack » quantum computer,* in prep.

Thanks! Theory group at Institut Néel



M. Fellous-Asiani, PhD

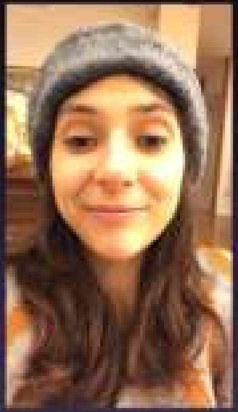
B. Goes, PhD



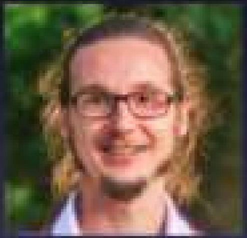
L. Bresque, PhD

J.H. Chai, post-doc

S. Wein, post-doc



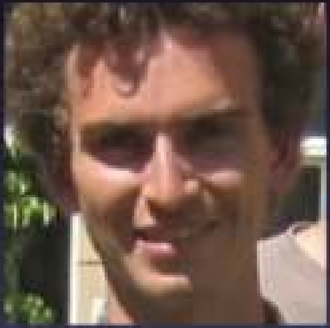
M. Maffei, post-doc



P. Camati, post-doc

N. Piccione, post-doc

S. Prasad, PhD



I. Frérot, post-doc

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