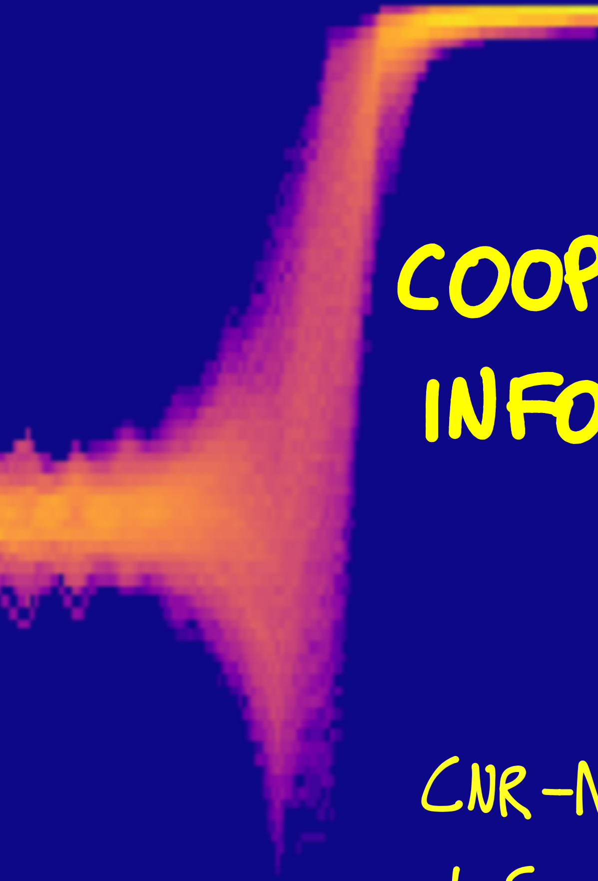

COOPERATIVE QUANTUM INFORMATION ERASURE

_ Michele Campisi _

CNR-Nano Science Institue
& Scuola Normale Superiore

quantum annealing time provided by

CINECA

project q-land

Quantum
the open journal for quantum science

Cooperative quantum information erasure

Lorenzo Buffoni[1,2] and Michele Campisi[3]

[1]Portuguese Quantum Institute, Lisbon, Portugal
[2]Department of Physics and Astronomy, University of Florence, 50019 Sesto Fiorentino, Italy
[3]NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

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Lorenzo Buffoni (Florence)

Qubit initialisation

(quantum information erasure)

$$\boxed{\text{any } \rho \longrightarrow \underbrace{|4\rangle\langle 4|}_{\text{pure}}}$$

energetic cost:

Piechocinska, PRE 61: 062314 (2000)

Esposito et al, NJP 12: 013013 (2010)

$$\boxed{W \geq T\Delta S}$$

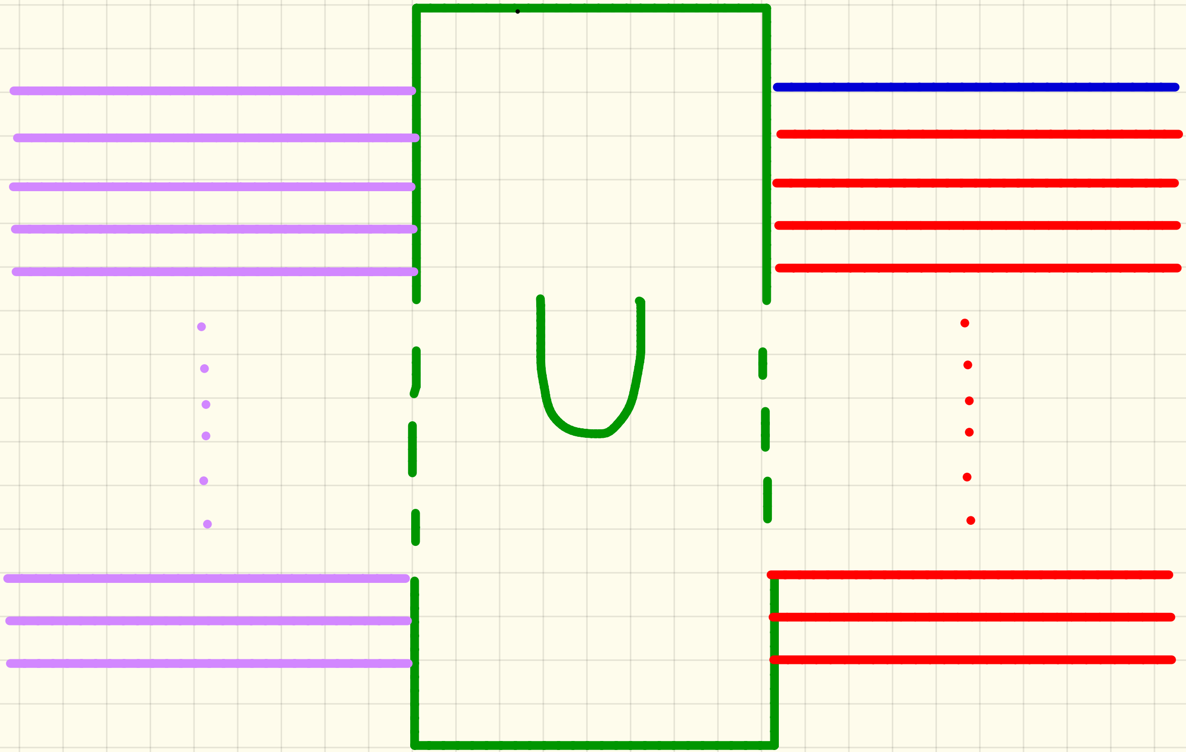
T = environment temperature

$$\Delta S = \mathrm{Tr}\, \rho \ln \rho$$

$$\left(\rho = \mathrm{Id}/2 \qquad \Delta S = \ln 2 \right)$$

standard (quantum info) approach: algorithmic cooling

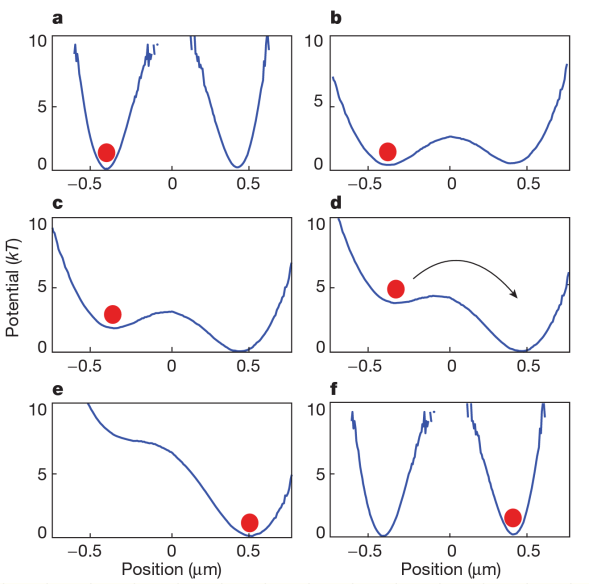
(quantum thermo) (quantum heat engine)

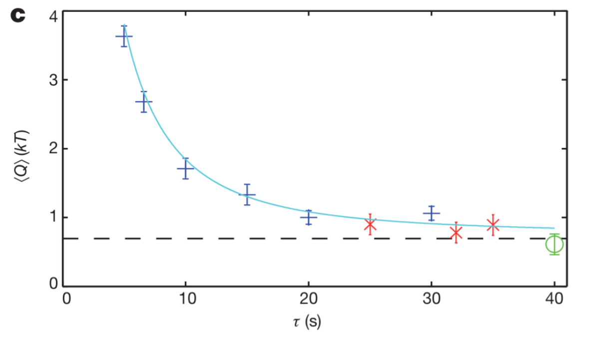


Landauer (1961)

minimal energy cost of writing (= resetting)
1 bit of information

$$\boxed{W = kT \ln 2}$$

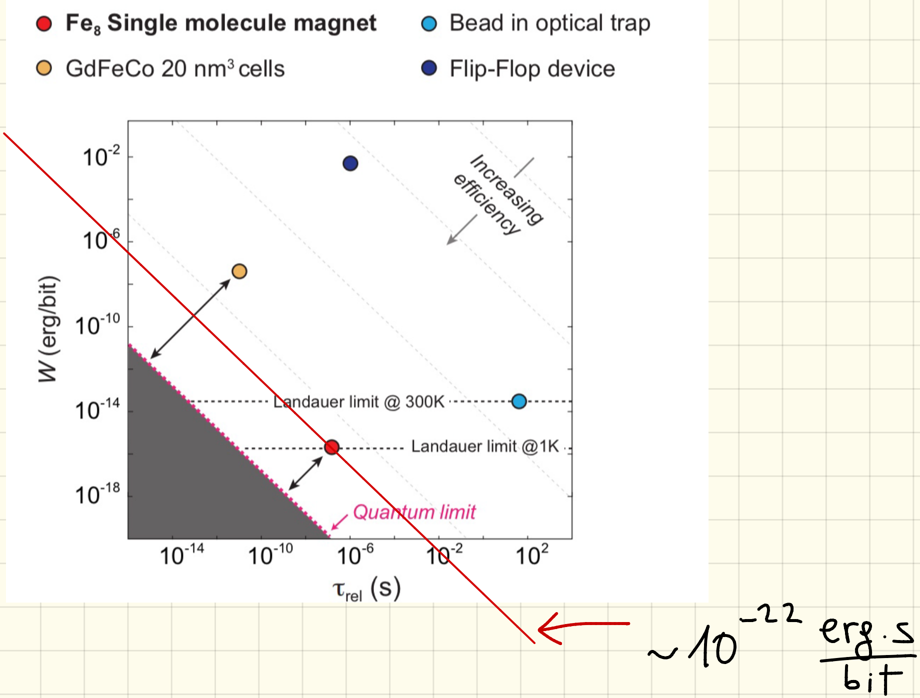




Berut et al. Nature 483 (7388) 187-189 (2012) figure of merit = erasing action

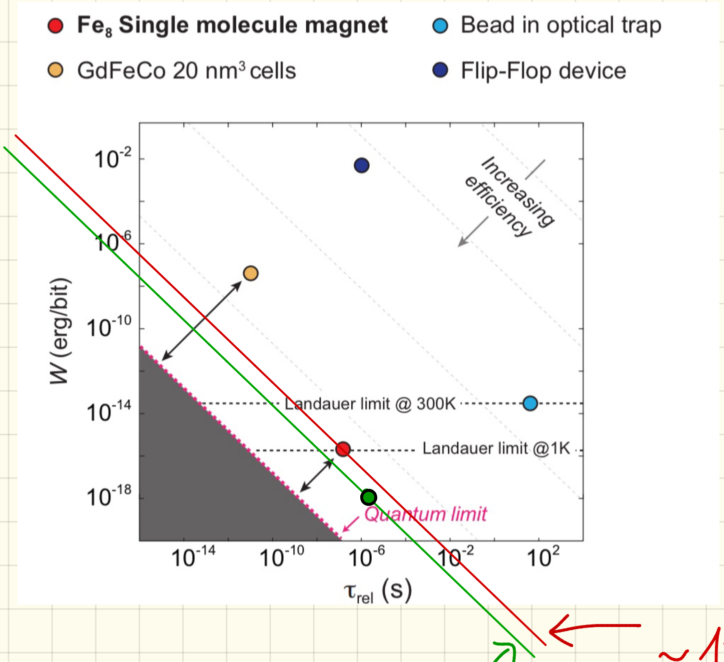
$$\boxed{A = \underbrace{w}_{\text{work per bit}} \cdot \underbrace{\tau}_{\text{erasure time}}}$$

Gaudenzi et al, Nat. Phys. 14 565 (2018)



Gaudenzi et al,
Nat. Phys. 14
565 (2018)

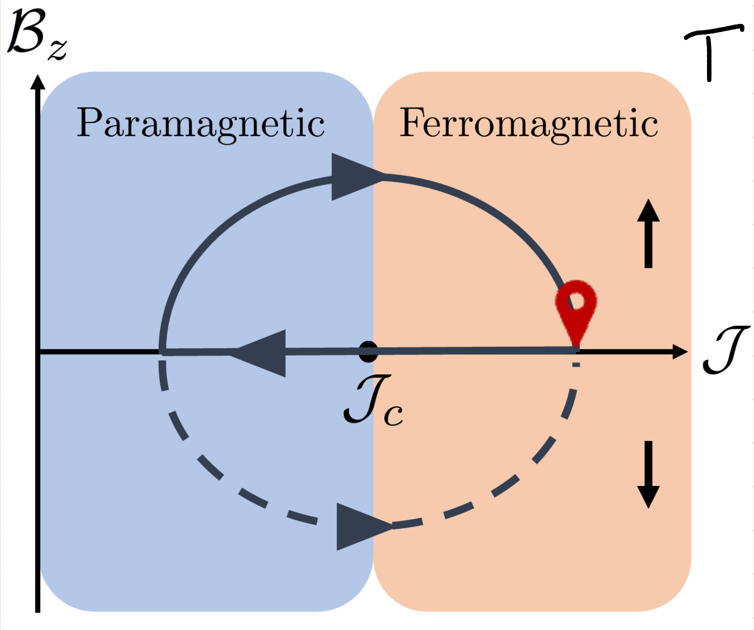
this work



$\sim 10^{-22} \, \frac{erg \cdot s}{bit}$ → Gaudenzi et al, Nat. Phys. 14 565 (2018)

$\sim 10^{-23} \, \frac{erg \cdot s}{bit}$ → this work

OUR MAIN IDEA:



$$H = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - B_z \sum_i \sigma_i^z$$

SPONTANEOUS SYMMETRY BREAKING + QUANTUM TUNNELING

Implementation: D-Wave 4.1 Advantage processor

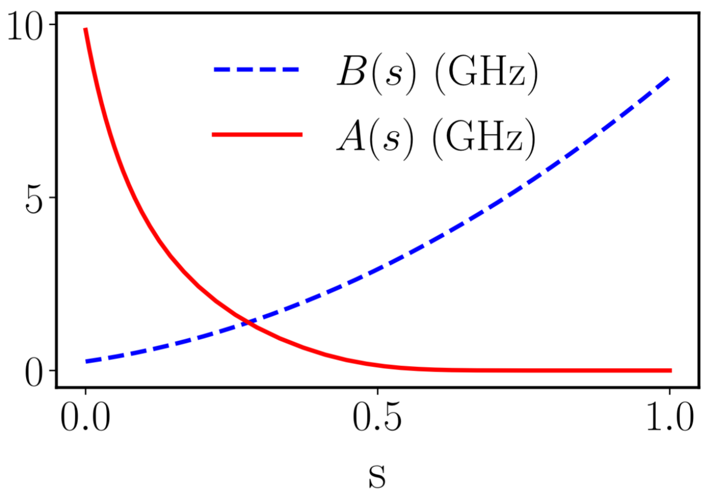
$$\frac{H(s)}{h} = -\frac{A(s)}{2}\sum_i \sigma_i^x - \frac{B(s)}{2}\left[g\sum_i \sigma_i^z + \sum_{i,j} J_{ij}\sigma_i^z\sigma_j^z\right]$$

$s \longrightarrow s(t)$

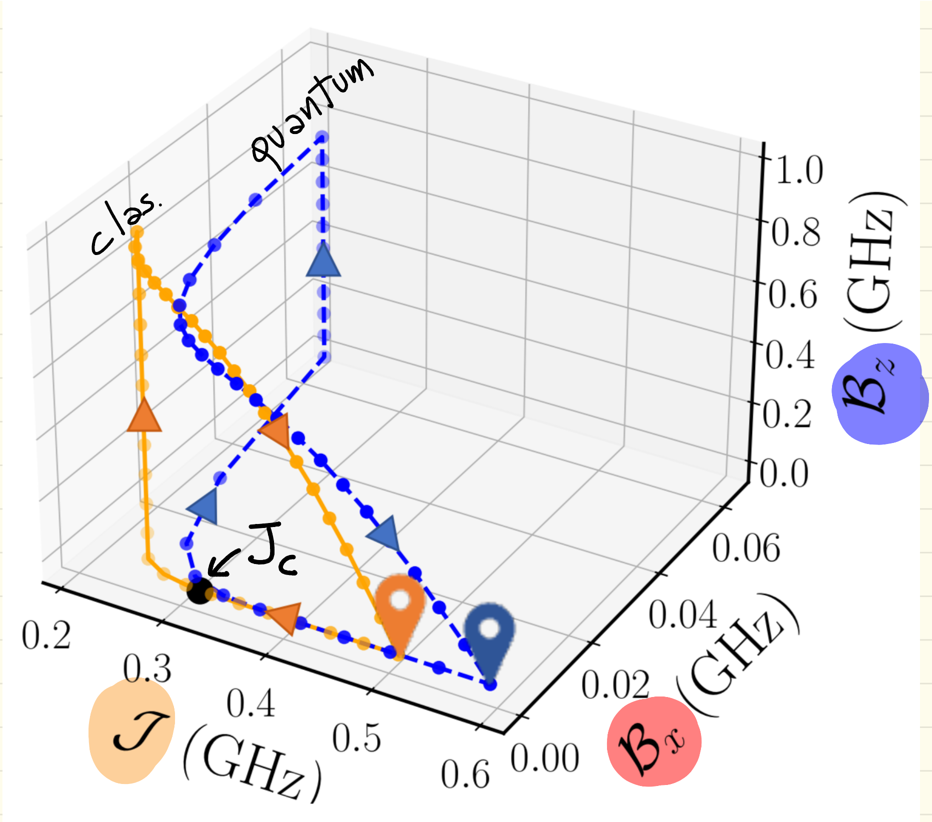
$g \longrightarrow g(t)$

$J_{ij} \longrightarrow$ constant

$N = 16 \times 16 = 256$



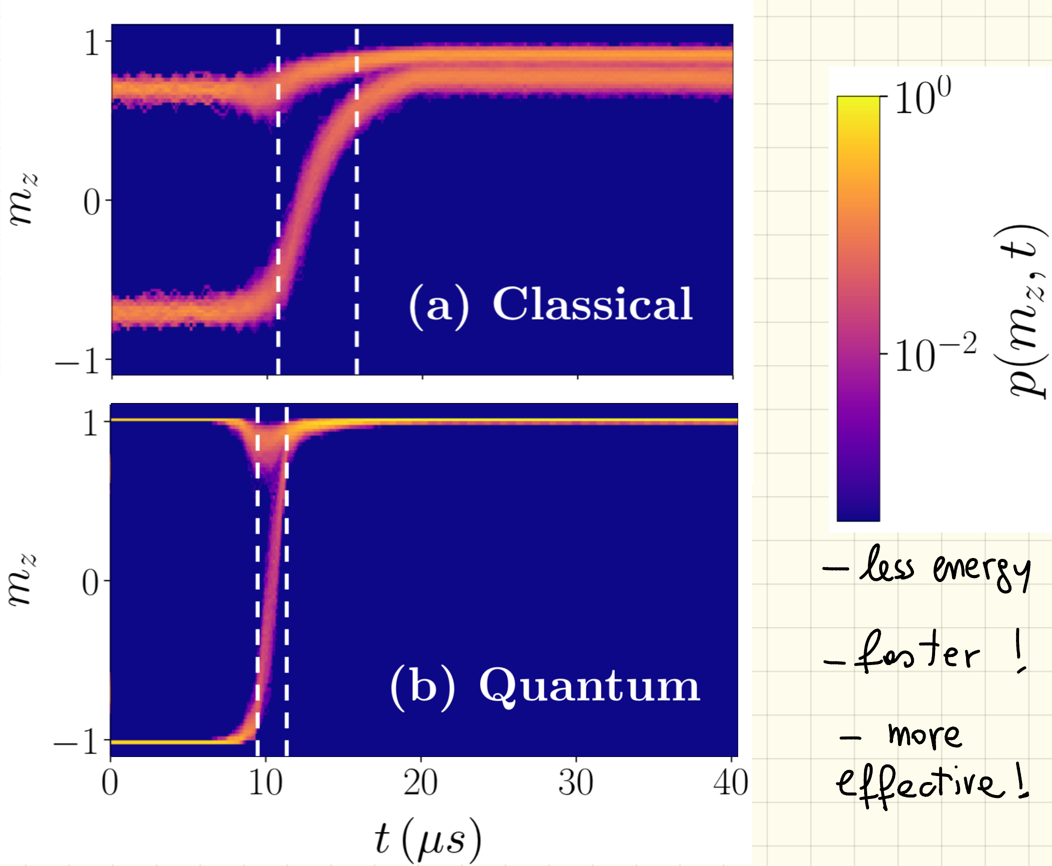
$$\frac{H(t)}{h} = -\mathcal{B}_x(t)\sum_i \sigma_i^x - \mathcal{B}_z(t)\sum_i \sigma_i^z - \mathcal{J}(t)\sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z$$



erasure of a single macroscopic bit

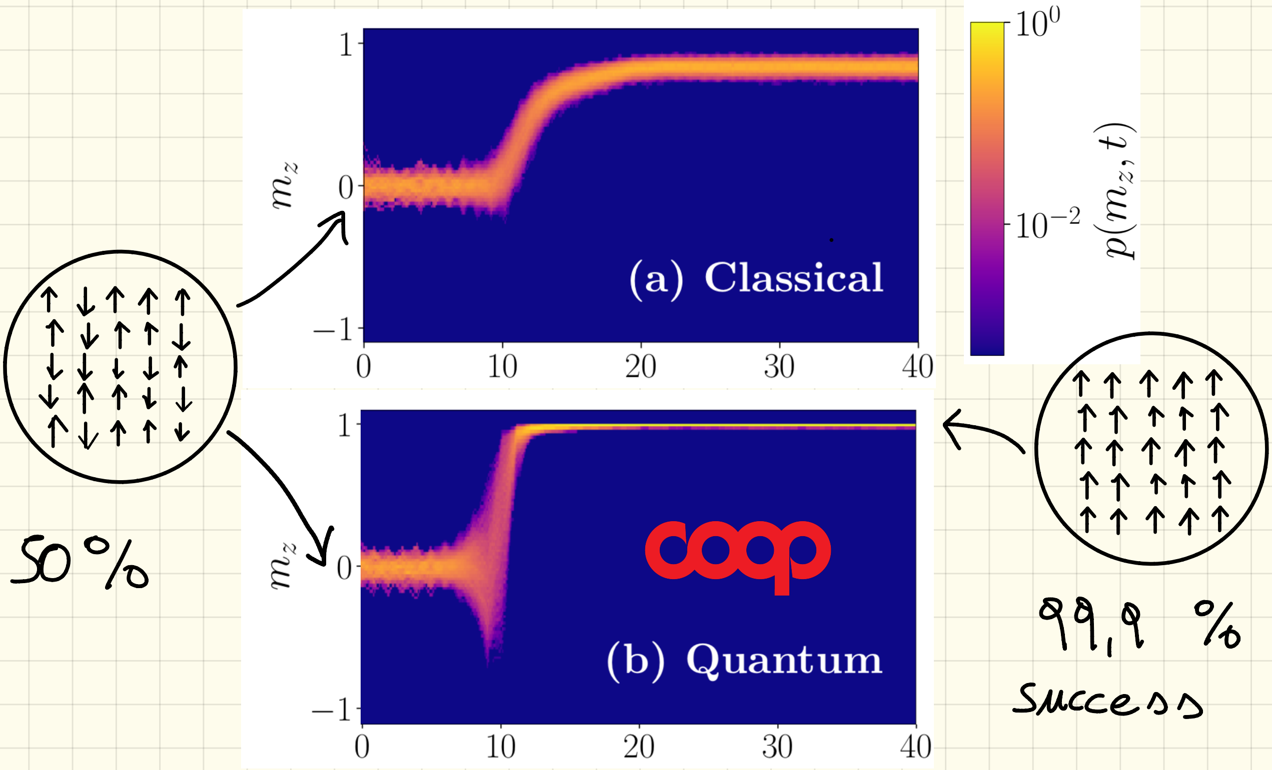
$$m_z = \frac{\sum_i s_i^z}{N}$$

$$\left(\begin{array}{c} \sigma_i^z |s_i^z\rangle = s_i^z |s_i^z\rangle \\ s_i^z = \pm 1 \end{array} \right).$$



- less energy !
- faster !
- more effective !

coop quantum erasure of N bits



$T_{spin} = \infty \xrightarrow{\text{cooling}} T_{spin} \simeq 0$

Energy Cost

$$W = \langle H^{TOT}(\tau)\rangle - \langle H^{TOT}(0)\rangle = \int_0^\tau dt \, \frac{d}{dt}\langle H^{TOT}\rangle = \int_0^\tau dt \left\langle \frac{\partial H^{TOT}}{\partial t}\right\rangle$$

$$= \int_0^\tau dt \left\langle \frac{\partial H}{\partial t}\right\rangle = \oint d\underline{R} \left\langle \frac{\partial H}{\partial \underline{R}}\right\rangle$$

$$\underline{R} = (B_x, B_z, J) \qquad \frac{\partial H}{\partial \underline{R}} = (M_x, M_y, K)$$

$$M_x = \sum_i \langle \sigma_i^x \rangle,\; M_z = \sum_i \langle \sigma_i^z \rangle,\; K = \sum_{\langle i,j\rangle} \langle \sigma_i^z \sigma_j^z \rangle$$

$$W = -\int_C \left(M_x d\mathcal{B}_x + M_z d\mathcal{B}_z + K d\mathcal{J} \right)$$

$$\doteq W_x + W_z + W_{zz}\,.$$

W_z, W_{zz} → directly from the s_i^z

W_x → cannot access s_i^x : bound its modulus

$$|M_x| = |\sum_i \langle \sigma_i^x \rangle| \leq \sum_i |\langle \sigma_i^x \rangle| \leq \sum_i \sqrt{1 - \langle \sigma_i^z \rangle^2} \doteq M_*$$

F = forward
B = backward

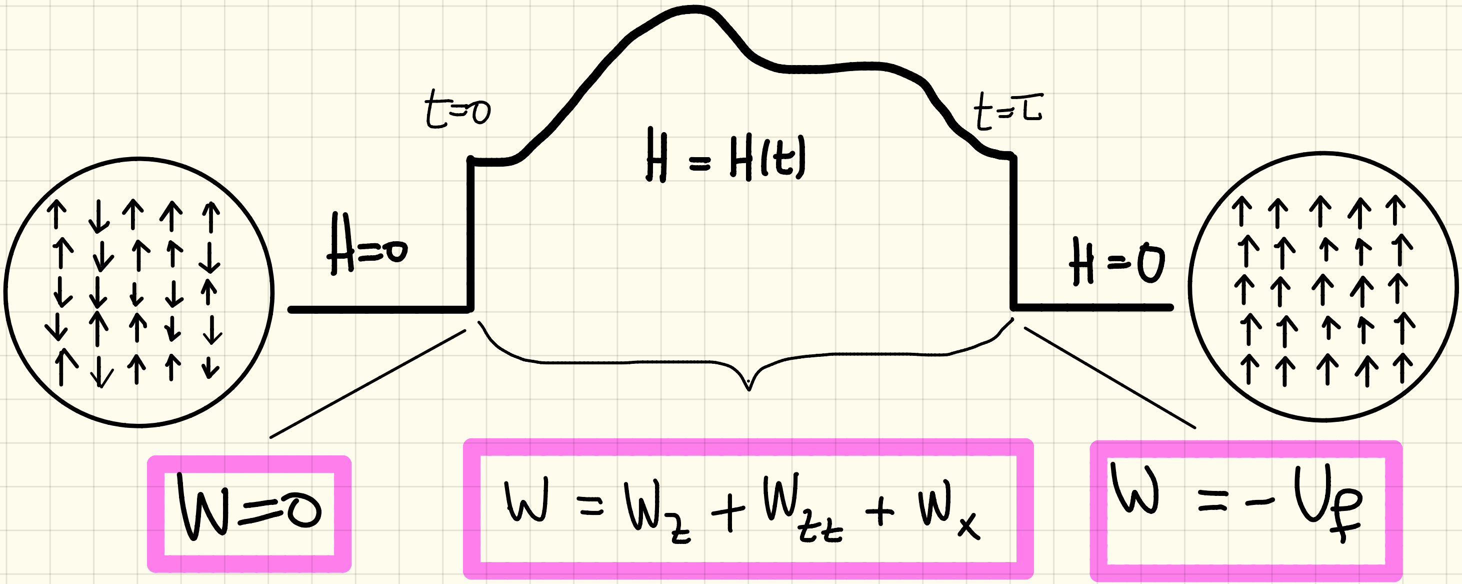
$$\begin{aligned} W_x &= -\int_{\mathcal{B}_x^{\min}}^{\mathcal{B}_x^{\max}} M_x^F d\mathcal{B}_x - \int_{\mathcal{B}_x^{\max}}^{\mathcal{B}_x^{\min}} M_x^B d\mathcal{B}_x \\ &= -\int_{\mathcal{B}_x^{\min}}^{\mathcal{B}_x^{\max}} (M_x^F - M_x^B) d\mathcal{B}_x \leq \int_{\mathcal{B}_x^{\min}}^{\mathcal{B}_x^{\max}} (|M_x^F| + |M_x^B|) d\mathcal{B}_x \\ &= \int_{\mathcal{B}_x^{\min}}^{\mathcal{B}_x^{\max}} (M_*^F + M_*^B) d\mathcal{B}_x \doteq \delta W \,. \end{aligned}$$

Same for $-W_x$

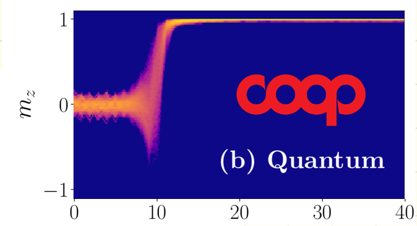
$\Rightarrow |W_x| \leq \delta W$

$$W_{\exp} = W_z + W_{zz} \pm \delta W$$ → from s_i^z

$$\frac{H(t)}{h} = -\mathcal{B}_x(t)\sum_i \sigma_i^x - \mathcal{B}_z(t)\sum_i \sigma_i^z - \mathcal{J}(t)\sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z$$



$$w = 3,55(0,73) \times 10^{-18} \text{erg/bit}$$



$$w_L = kT \ln 2 = 3,7(0,8) \times 10^{-18} \text{erg/bit}$$

$(T = 39 \pm 9 \text{ mK})$

$$\tau_{99,9} \cong 9 \ \mu s$$

$$\mathcal{A}_{99,9\%} = 3.19(0.27) \times 10^{-23} \text{erg} \cdot \text{s/bit}$$

Remarks

1) Erasure occurs @ minimal energy cost (within error)

2) Lowest erasure action reported to date (To the best of our knowledge)

3) Very high success rate : 99,9 %

4) Very stable bit reset : at least order of seconds

5) Not optimised → room for improvement.

Remarks

6) Erase all N qubits at once (algorithmic cooling erases a fraction)

7) Expected to work the better the larger N !!

8) Application: initialisation of quantum processing units

9) Openness was crucial for achieving purification

"mixedness" was dump into environment!

-- all this thanks to a shift in cooling paradigm

SYNERGY OF COOPERATIVE

EMERGENT MANY-BODY EFFECTS

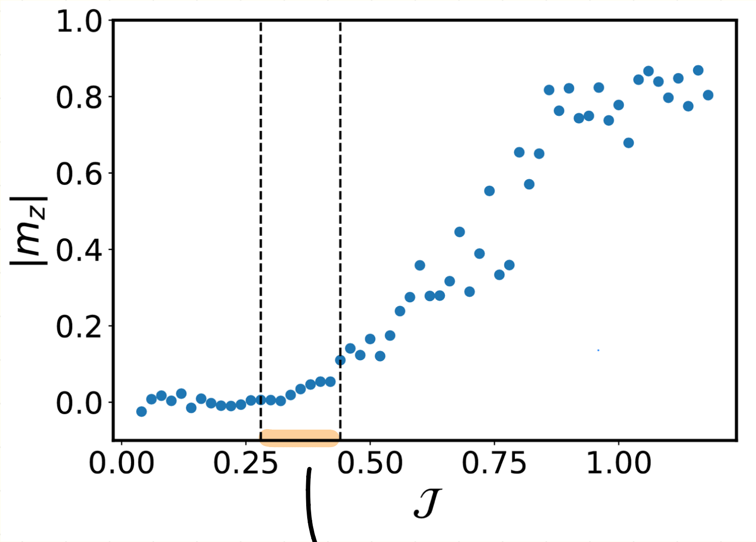
(spontaneous Symmetry breaking)

&

QUANTUM EFFECTS

Thanks

Estimating the Temperature



J_c

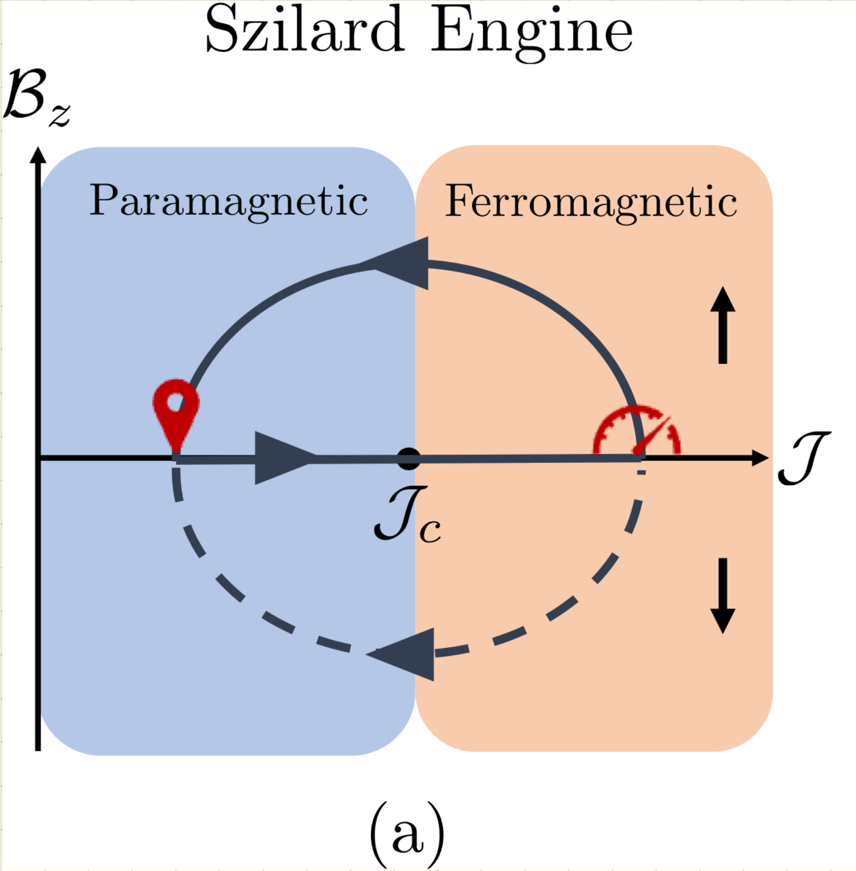
$$s(t) = \frac{t}{\tau} \qquad \tau = 200\ \mu s$$

$@\ g = 0$

$$\frac{H(s)}{h} = -\frac{A(s)}{2}\sum_i \sigma_i^x - \frac{B(s)}{2}\left[\sum_{i,j} J_{ij}\sigma_i^z\sigma_j^z\right]$$

$$kT = \frac{2\,J_c}{\ln(1+\sqrt{2})}$$

erg $\times 10^{-18}$	Classical er.	Quantum er.	Qu. coop. er.
W_z	1067(80)	331(66)	166(60)
W_{zz}	-351(86)	-9.3(13)	-1140(20)
δW	36	53	106
U_f			-1884
W_{exp}	716(202)	322(132)	910(186)
W_L	3.71(0.79)	3.71(0.79)	949(202)



J. Parrondo,
Chaos 11, 725 (2001)

$$\boxed{H = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - B_z \sum_i \sigma_i^z}$$

Quantum energy advantage ?

Quantum Technologies Need a Quantum Energy Initiative

Alexia Auffèves

PRX Quantum **3**, 020101 – Published 1 June 2022

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https://quantum-energy-initiative.org