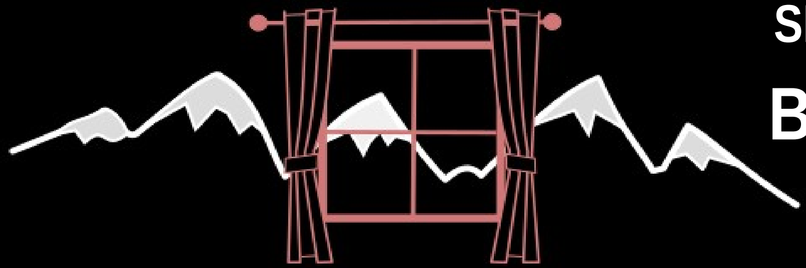
Laboratoire de Physique et Modélisation des Milieux Condensés
Université Grenoble Alpes & CNRS

Illusory Cracks in the 2nd Law of Thermodynamics in Quantum Nanoelectronics

Failles illusoires dans la 2ème principe de la thermodynamique dans la nanolectronique quantique

Robert S. Whitney

Habilitation Defence: 21 November 2022 (Grenoble)



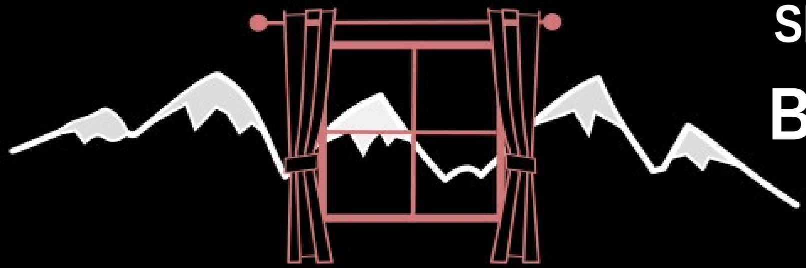
SMALL WINDOW ONTO
BIG LANDSCAPE

Quantum Physics

THERMODYNAMICS & stat phys
155 years since Maxwell's demon
(Boltzmann theory, etc)

FUNDAMENTAL QUESTIONS
2^{nd} law of thermodynamics
as *emergent* phenomenon
→ *Arrow of Time*

TECHNOLOGICAL QUESTIONS
Efficiencies of machines



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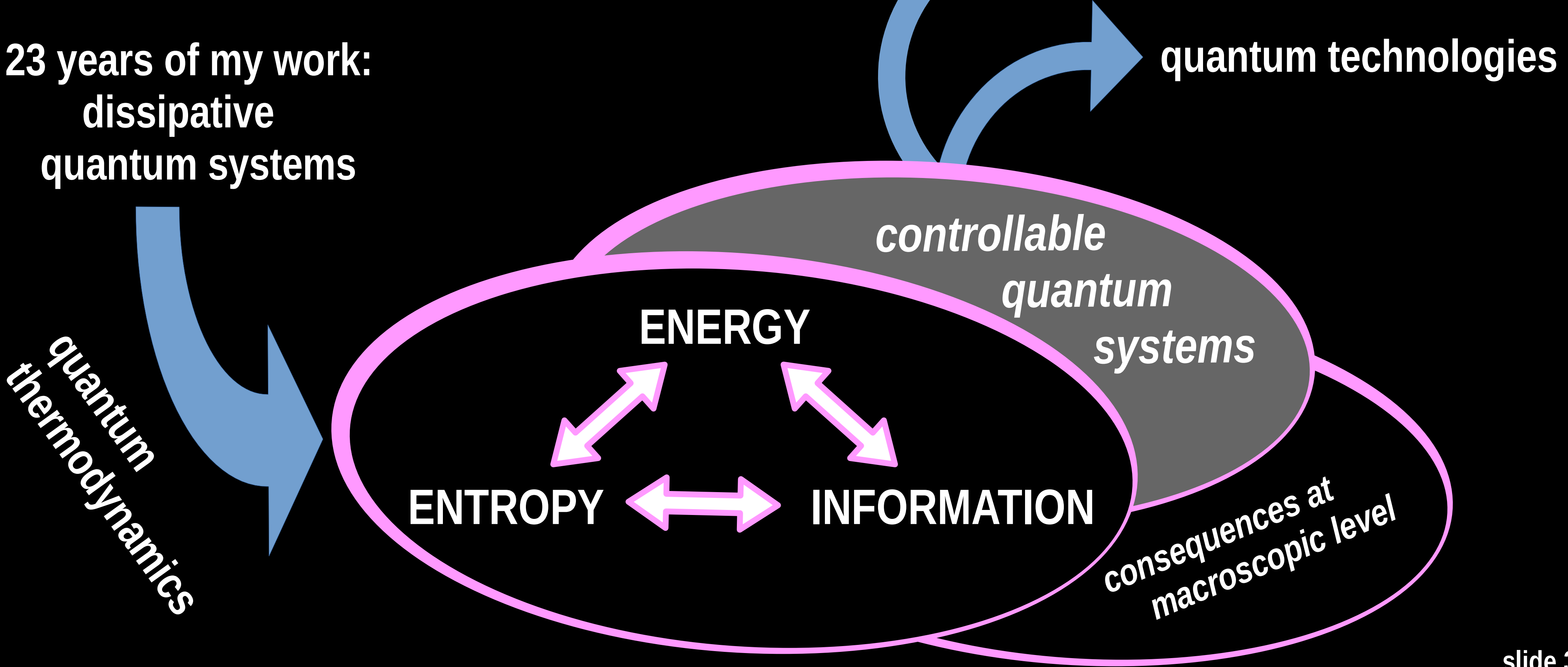
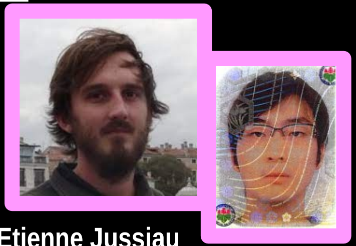


SMALL WINDOW ONTO
BIG LANDSCAPE

Federica Haupt, Janine Splettstoesser & Rafael Sanchez



Etienne Jussiau & Masahiro Hasegawa (PhDs 2015-2018)

Nanoelectronics & dissipative quantum systems

Alexia Auffeves, Hui Khoon Ng, Jing Hao Chai, Marco Fellous-Asiani (PhD 2018-2021)

Igor Lerner

Yuval Gefen

John Chalker

Philippe Jacquod

Markus Buttiker

1995 2000 2005 2010

Rob Smith

Holger Schanz

Greg Berkolaiko

Sasha Shnirman & Yuriy Makhlin

Cyril Petitjean (PhD 2005 - 2008)

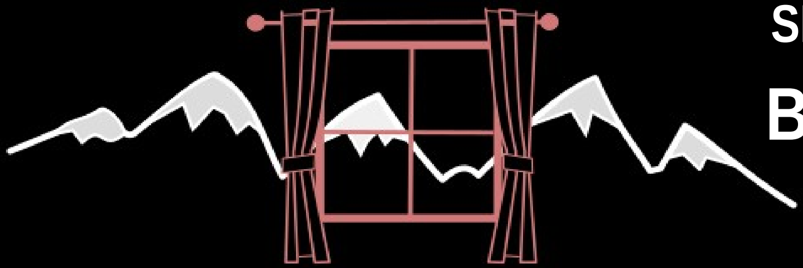
Massimo Macucci & Paolo Marconini

Dominique Bicout, Sasha Petukhov & Efim Kats

Maxim Clusel & Tim Ziman

Giulio Casati, Giuliano Benenti & Keiji Saito

slide 4

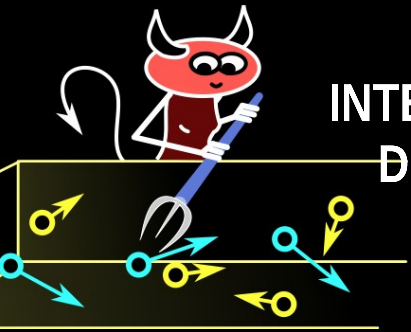


SMALL WINDOW ONTO
BIG LANDSCAPE

Smoluchowski (1912)

James Clerk Maxwell
(approx 1867)

DEMON
breaking 2nd law



INTELLIGENT
DEMON

MECHANICAL
DEMON

see works of (1) R. Lopez, (2) B. Huard (3) M. Esposito

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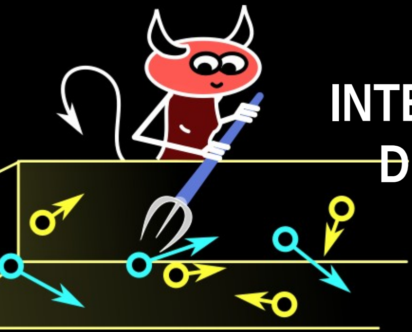


INTELLIGENT
DEMON

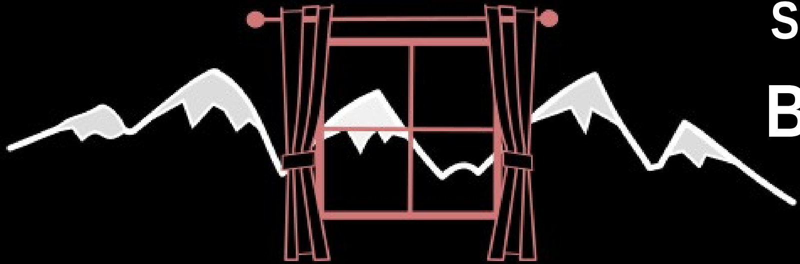
~~MECHANICAL
DEMON~~

Smoluchowski (1912)

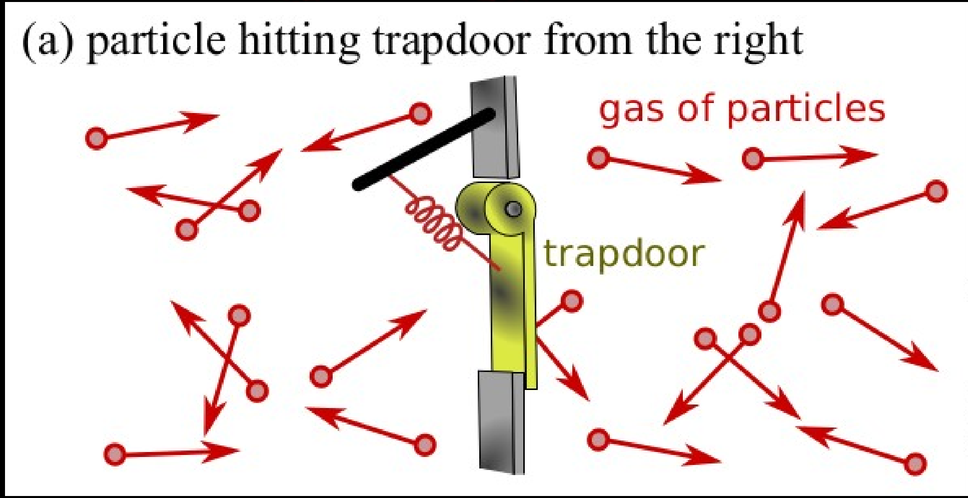
IMPORTANCE OF
FLUCTUATON

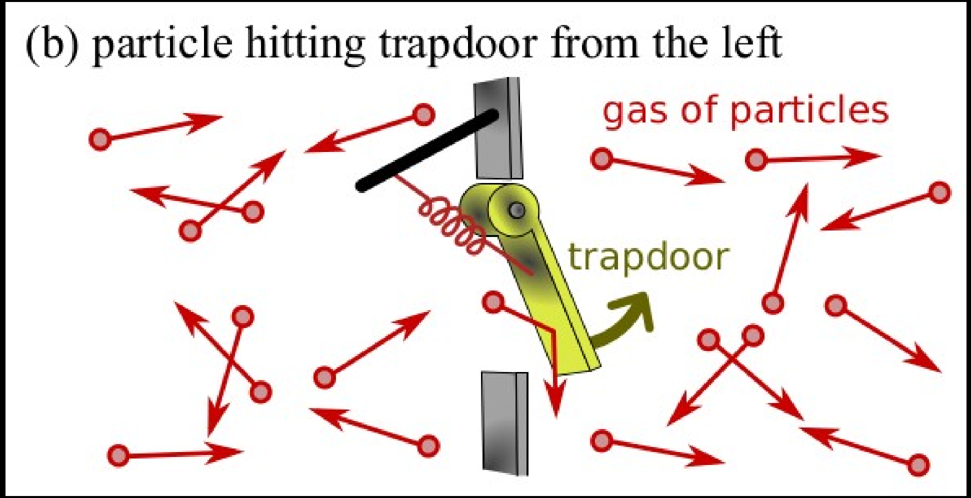
Modern Definition:
2nd law as
average property

see works of (1) R. Lopez, (2) B. Huard (3) M. Esposito



SMALL WINDOW ONTO
BIG LANDSCAPE





James Clerk Maxwell (about 1867) in letter to Tait:

"... less intelligent demons can produce a difference in pressure
... by merely allowing all particles going in one direction ... a ***valve*** ..."

Simply invoking trapdoor’s thermal motion

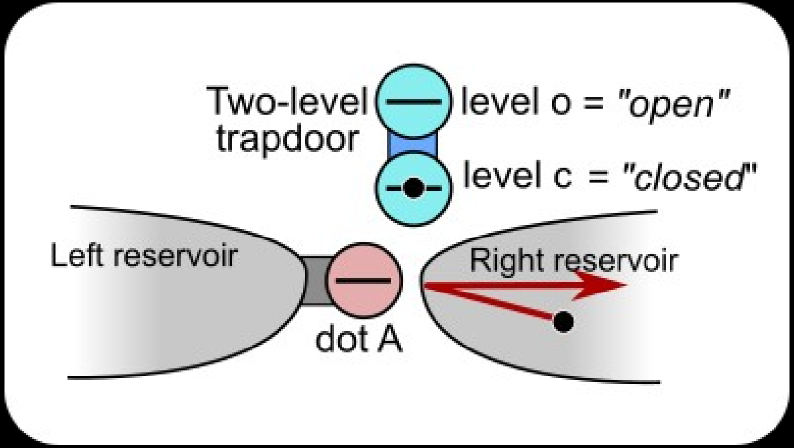
is NOT enough

to restore the 2nd law of thermodynamics

Skordos & Zurek (1998) Computer simulation of Smoluchowski’s trapdoor.

Quantum System: two-state trapdoor

(a) Electron arrives from RIGHT



Inspired by:
Strasberg, Schaller, Brandes & Esposito (2013).
Thermodynamics of a Physical Model Implementing a Maxwell Demon

Quantum System: two-state trapdoor

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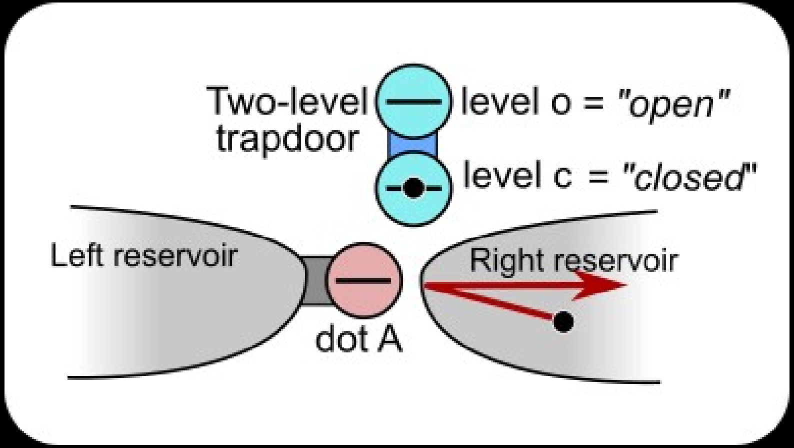
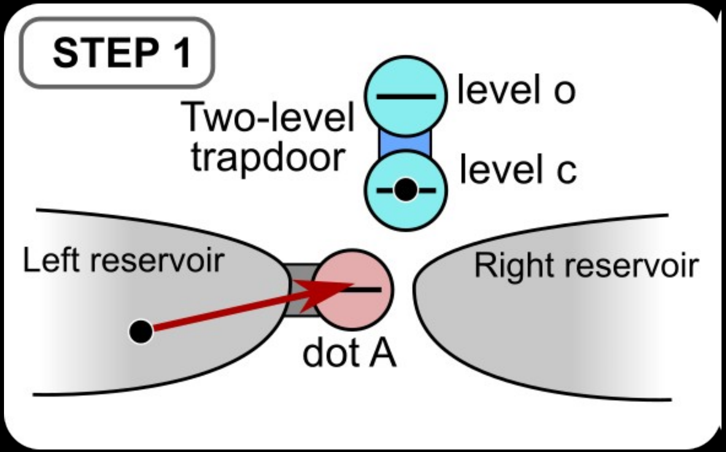
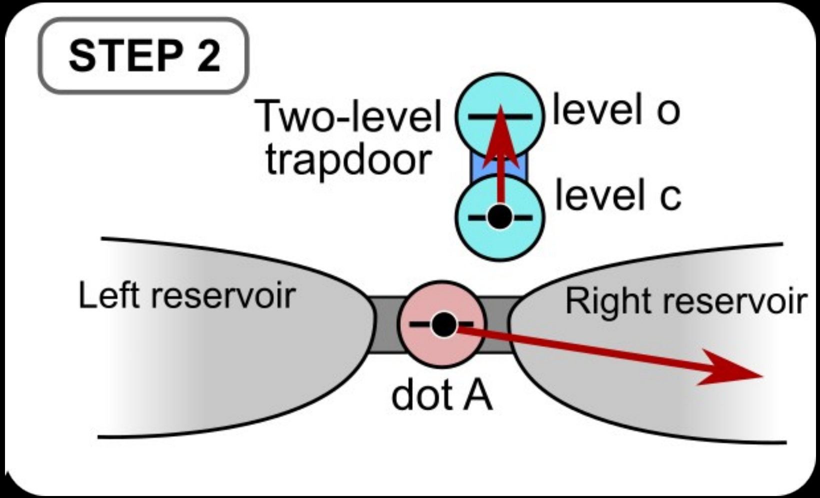


(b) Electron arrives from LEFT





Inspired by:
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Thermodynamics of a Physical Model Implementing a Maxwell Demon

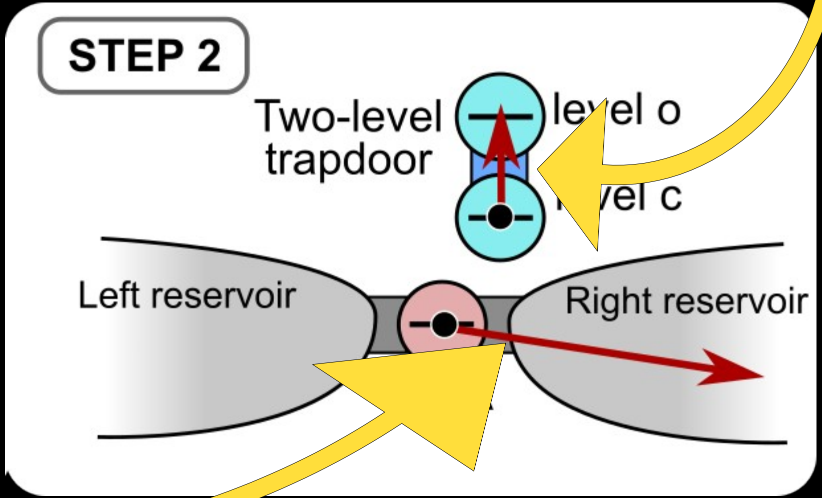
Quantum System: two-state trapdoor

Hamiltonian dot A & trapdoor

$$\hat{H}_{\rm sys} = E_{\rm A}\hat{d}_{\rm A}^{\dagger}\hat{d}_{\rm A} + E_{\rm c}\hat{d}_{\rm c}^{\dagger}\hat{d}_{\rm c} + E_{\rm o}\hat{d}_{\rm o}^{\dagger}\hat{d}_{\rm o} + \gamma\left(\hat{d}_{\rm c}^{\dagger}\hat{d}_{\rm o} + \hat{d}_{\rm o}^{\dagger}\hat{d}_{\rm c}\right) + U\hat{d}_{\rm A}^{\dagger}\hat{d}_{\rm A}\hat{d}_{\rm c}^{\dagger}\hat{d}_{\rm c}$$

Hamiltonian tunneling dot A to reservoirs

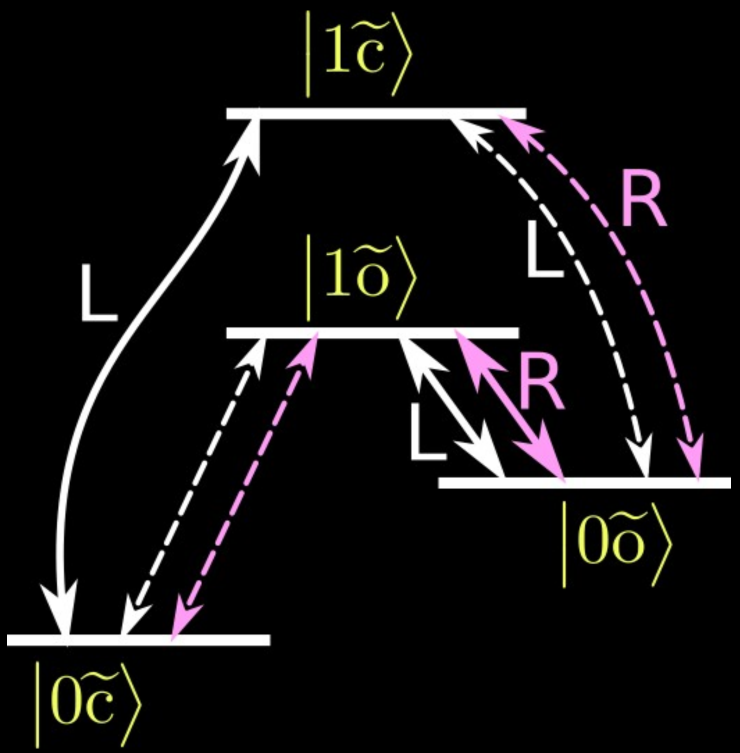
$$= \sum_p \gamma_p^{(\rm L)}\left(\hat{c}_{{\rm L};p}^{\dagger}\hat{d}_A + \hat{d}_A^{\dagger}\hat{c}_{{\rm L};p}\right) + \gamma_p^{(\rm R)}\hat{d}_{\rm o}^{\dagger}\hat{d}_{\rm o}\left(\hat{c}_{{\rm R};p}^{\dagger}\hat{d}_A + \hat{d}_A^{\dagger}\hat{c}_{{\rm R};p}\right)$$

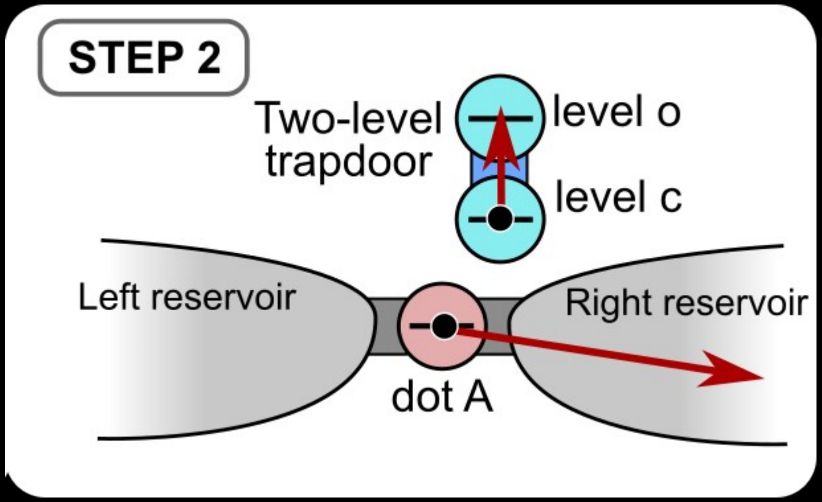


Hamiltonian reservoirs

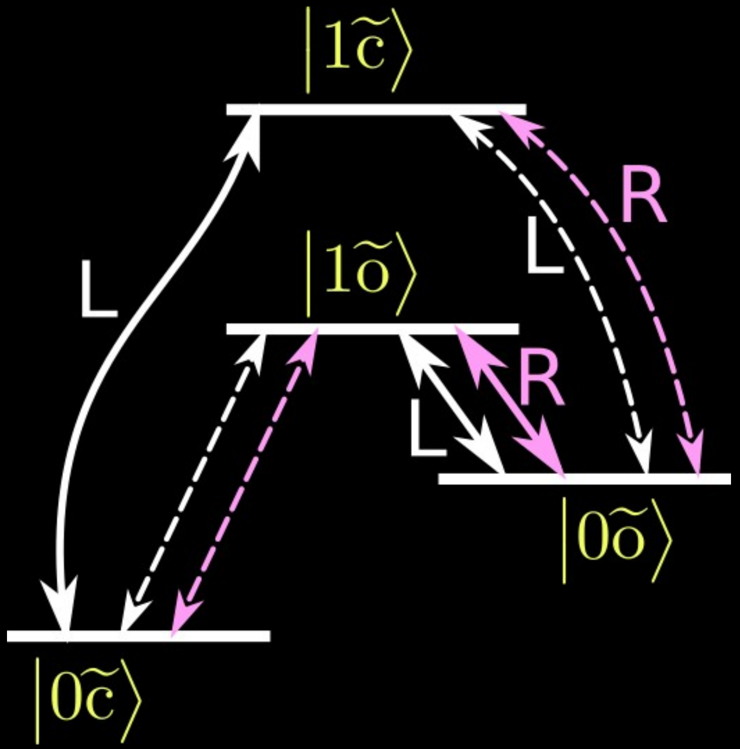
$$= \sum_p \epsilon_p^{(\rm L)}\hat{c}_{{\rm L};p}^{\dagger}\hat{c}_{{\rm L};p} + \epsilon_p^{(\rm R)}\hat{c}_{{\rm R};p}^{\dagger}\hat{c}_{{\rm R};p}$$

Quantum System: two-state trapdoor





Quantum System: two-state trapdoor



Fermi golden-rule approx for probability of each state, P_i

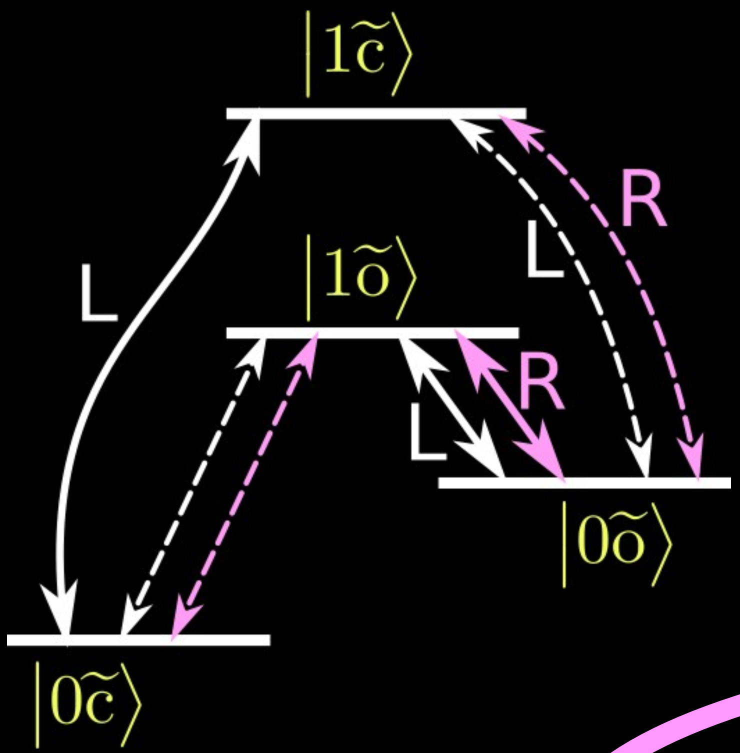
★ *eliminate coherent quantum superpositions*

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix} = \begin{pmatrix} \mathtt{A} & \mathtt{0} & \mathtt{B} & \mathtt{C} \\ \mathtt{0} & \mathtt{D} & \mathtt{E} & \mathtt{F} \\ \mathtt{G} & \mathtt{H} & \mathtt{I} & \mathtt{0} \\ \mathtt{J} & \mathtt{K} & \mathtt{0} & \mathtt{L} \end{pmatrix} \begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix}$$

where $\mathtt{E} = \mathtt{E}_\mathrm{L} + \mathtt{E}_\mathrm{R}$, etc.

Bloch-Redfield (1957)
advanced by others since
including (i) S. Florens & (ii) M. Wegewijs
see also our 2017 review

Quantum System: two-state trapdoor



Fermi golden-rule approx for probability of each state, P_i

★ *eliminate coherent quantum superpositions*

$$\frac{d}{dt}\begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix} = \begin{pmatrix} A & 0 & B & C \\ 0 & D & E & F \\ G & H & I & 0 \\ J & K & 0 & L \end{pmatrix} \begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix}$$

where $E = E_L + E_R$, etc.

Matrix elements obey LOCAL DETAILED BALANCE

e.g. $$H_L = E_L \exp\left[-\frac{\epsilon - \mu_L}{k_B T_L}\right]$$

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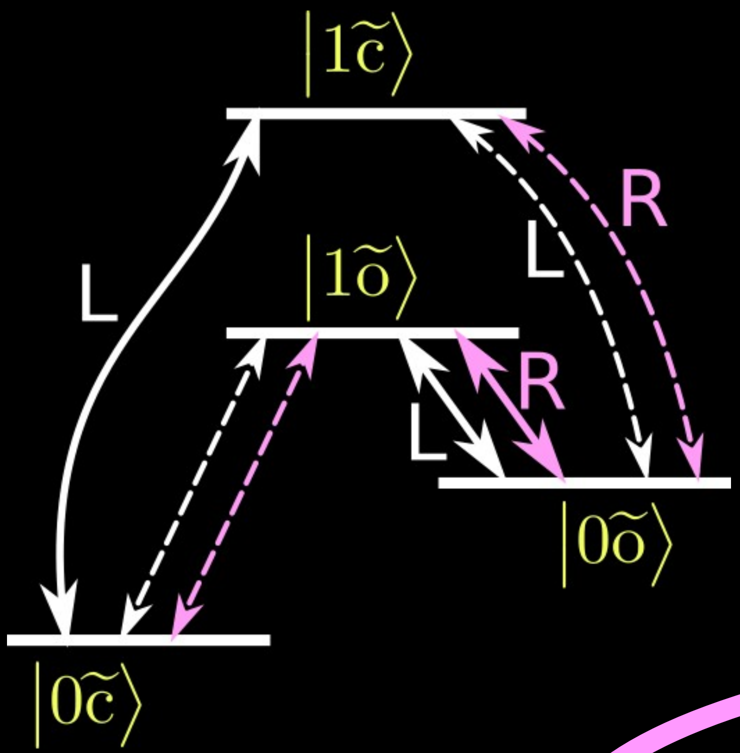
Quantum System: two-state trapdoor



Fermi golden-rule approx for probability of each state, P_i

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$$\frac{d}{dt}\begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix} = \begin{pmatrix} A & 0 & B & C \\ 0 & D & E & F \\ G & H & I & 0 \\ J & K & 0 & L \end{pmatrix} \begin{pmatrix} P_{0\tilde{c}} \\ P_{0\tilde{o}} \\ P_{1\tilde{o}} \\ P_{1\tilde{c}} \end{pmatrix} = 0$$

steady-state

where $E = E_L + E_R$, etc.

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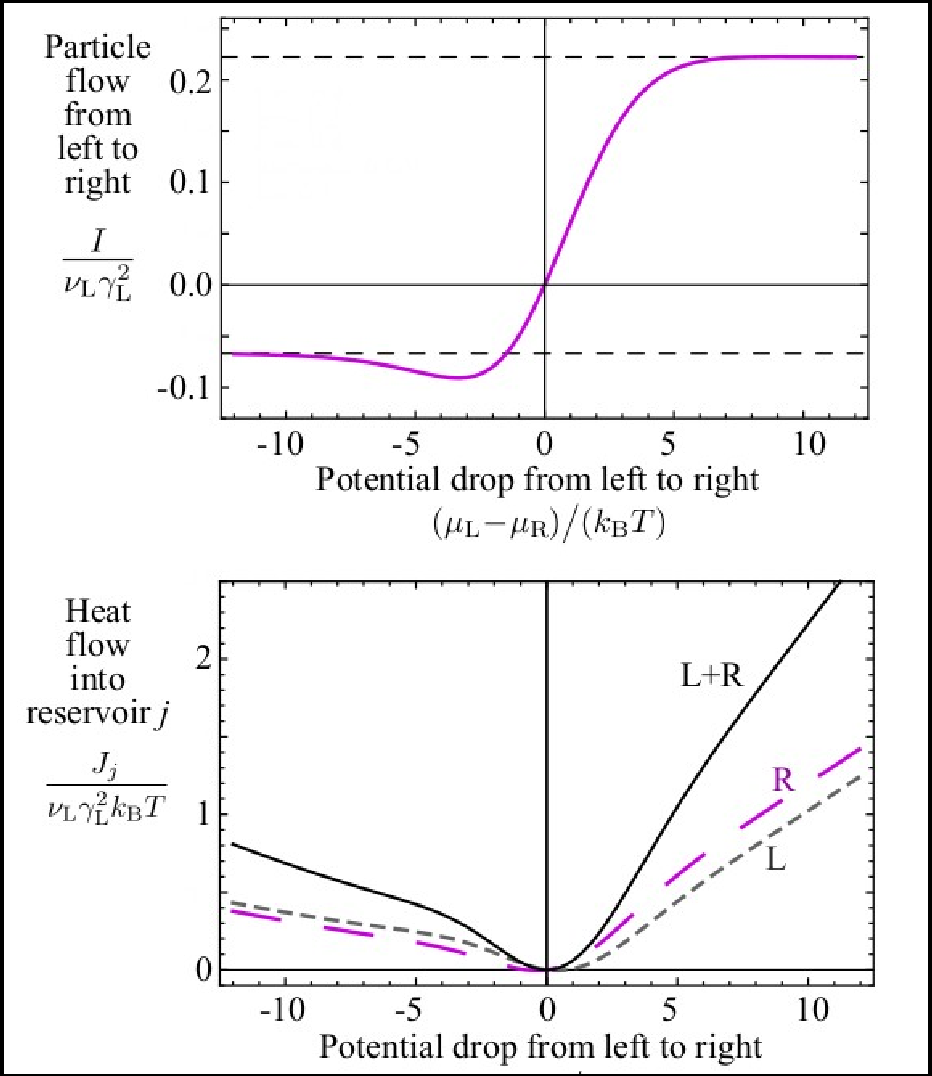
Quantum System: two-state trapdoor

- ✗ Does NOT turn heat (thermal fluctuations) into electrical power,

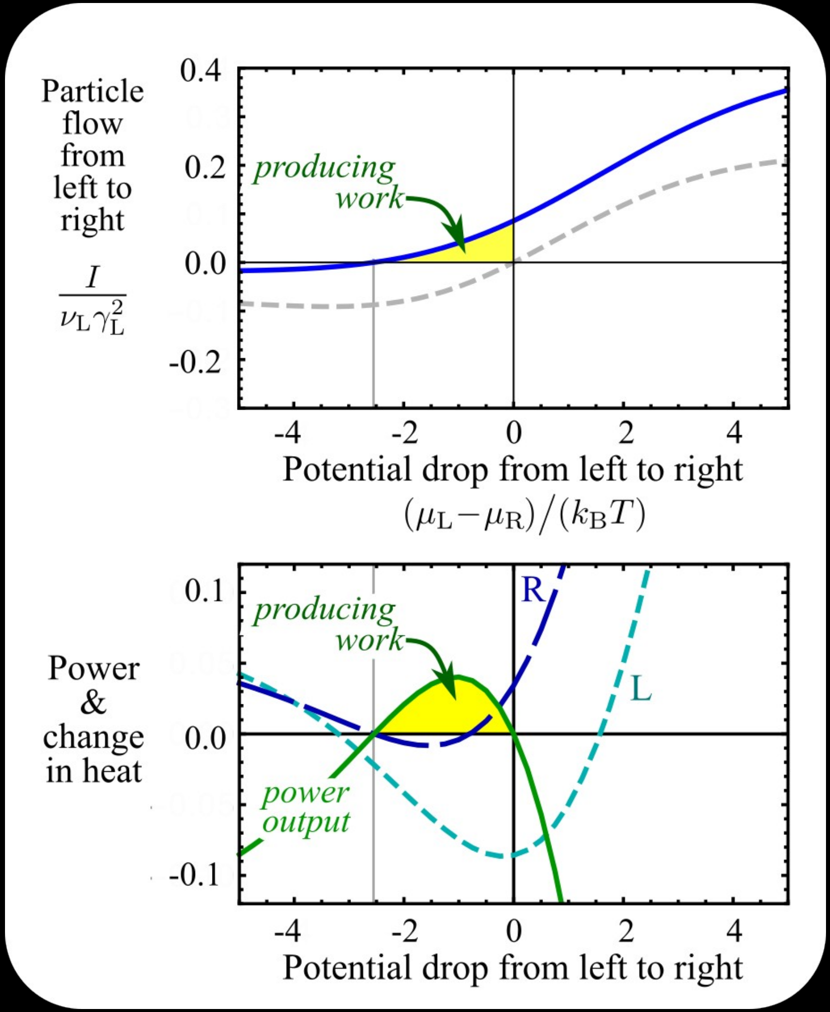
  ... instead it turns power into heat

- ✓ Obeys 2nd law of thermodynamics

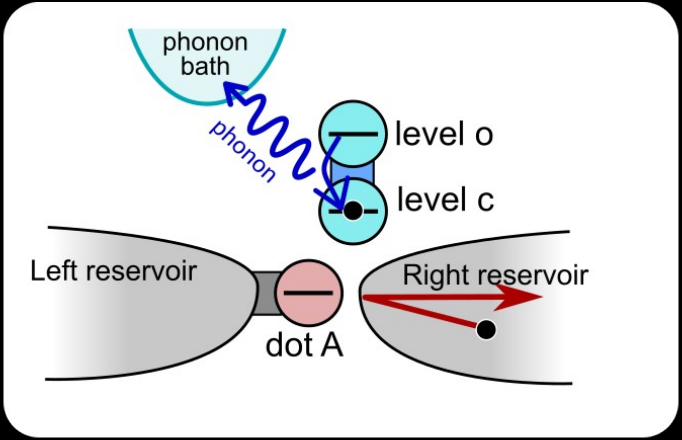
- ✓ Acts as diode

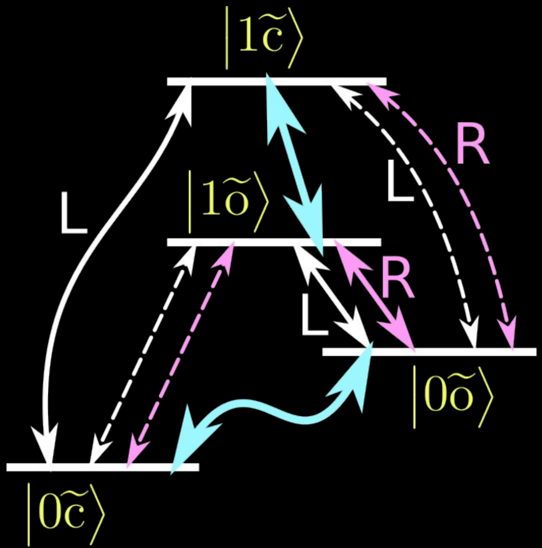


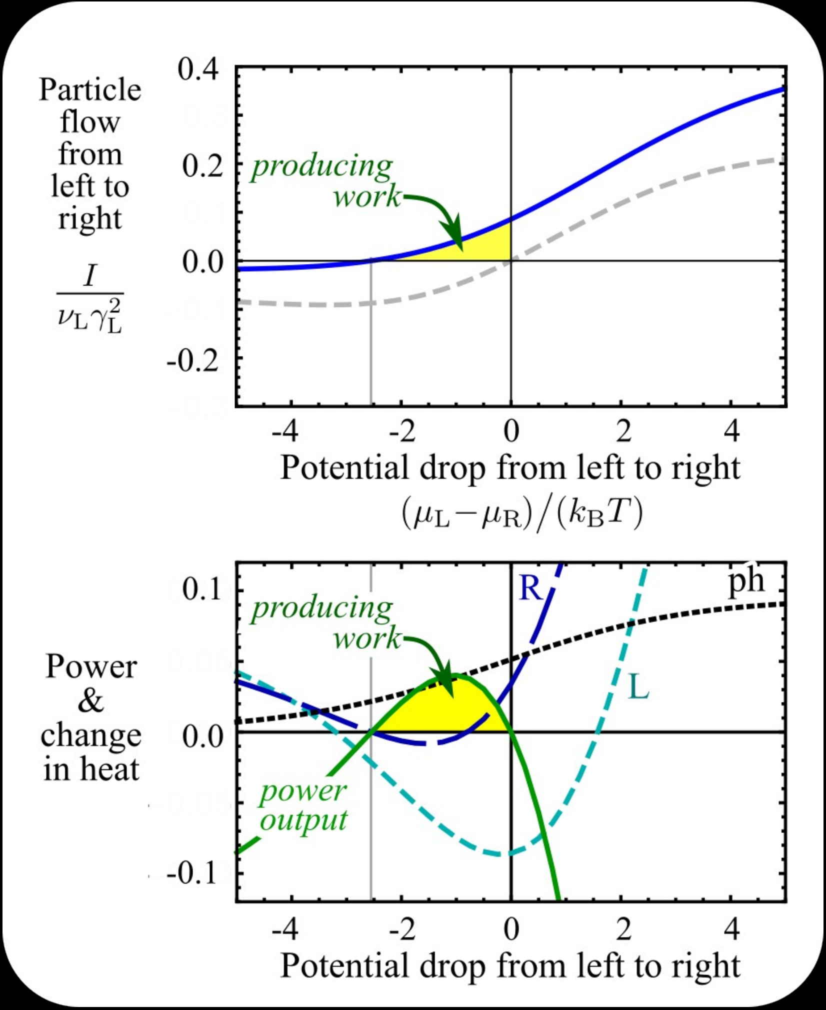
Quantum System: two-state trapdoor WITH DAMPING



Quantum System: two-state trapdoor WITH DAMPING







Inspired by:
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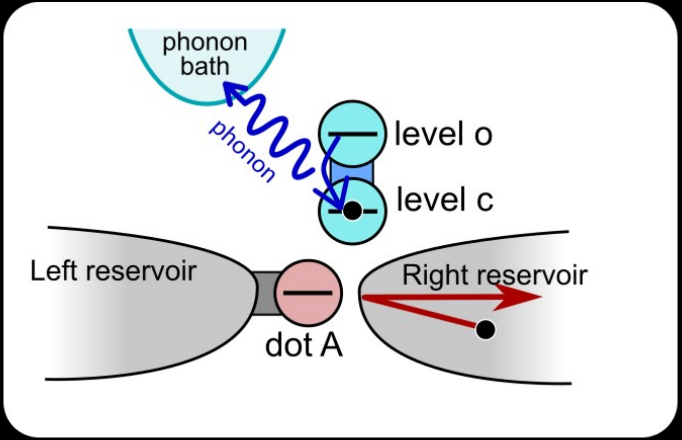
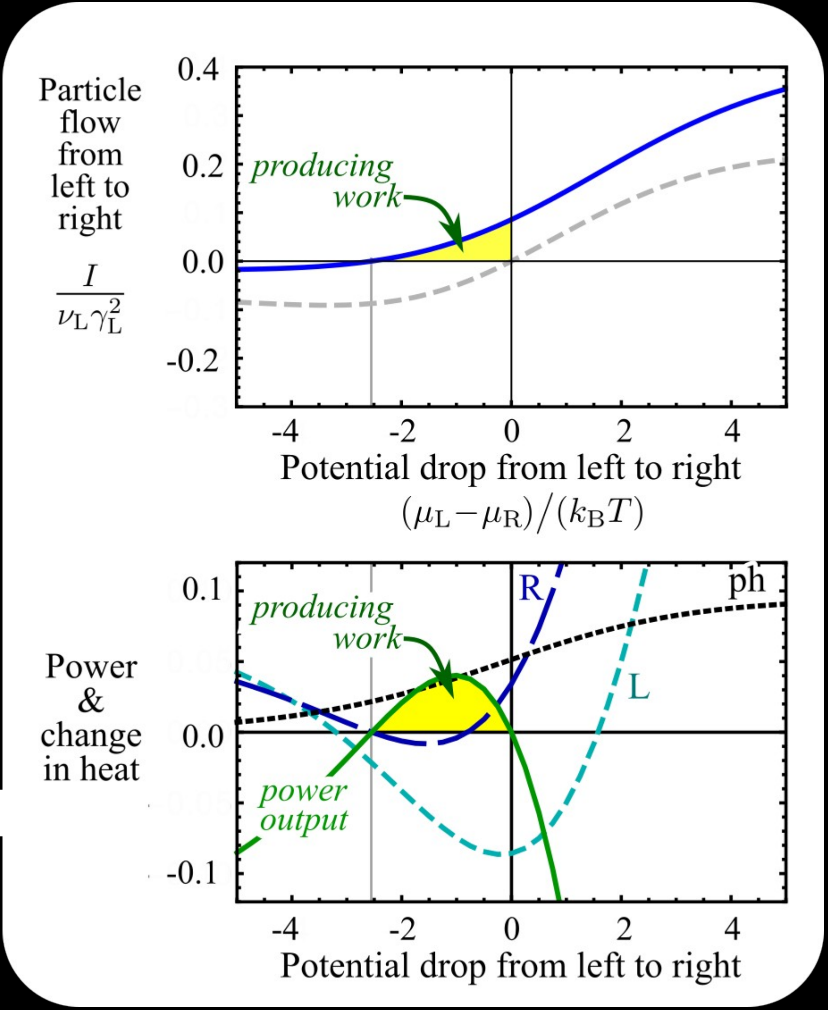
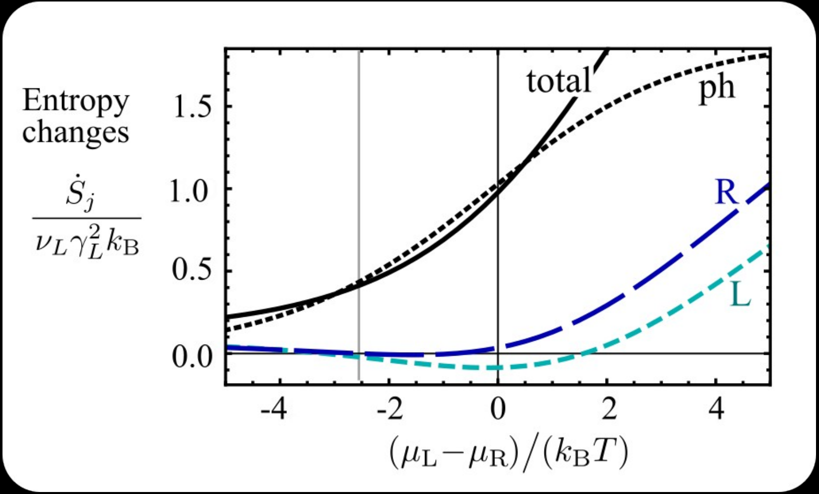
Quantum System: two-state trapdoor WITH DAMPING







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Strasberg, Schaller, Brandes & Esposito (2013).

ACTUALLY I HAVE CHEATED YOU:

2[nd] law is **AUTOMATICALLY** obeyed by any system obeying
rate equations without coherences + local-detailed balance

Proof: Schmiedl &Seifert (2007), reviewed by Van den Broeck & Esposito (2015)

BUT WHAT ABOUT QUANTUM SYSTEM that have **COHERENCES** ?

i.e. coupling to reservoirs is too strong for Fermi golden-rule approx (hence memory effects)

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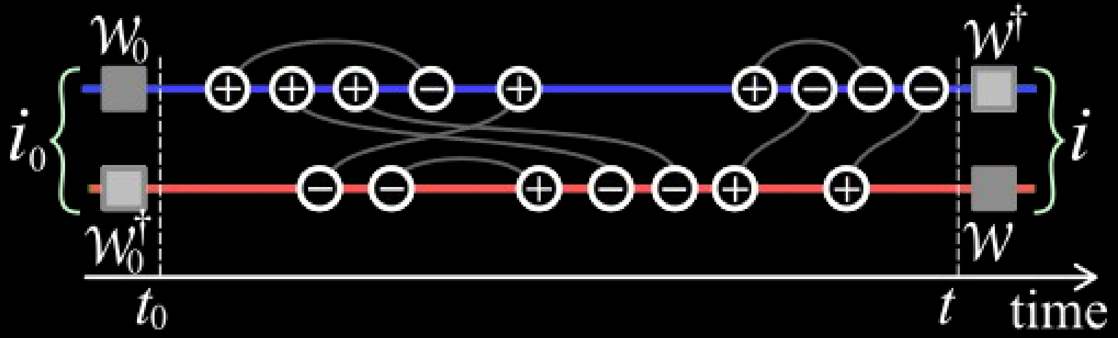
BUT WHAT ABOUT QUANTUM SYSTEM that have COHERENCES ?

i.e. coupling to reservoirs is too strong for Fermi golden-rule approx (hence memory effects)

For that I managed to prove 2^{nd} law is AUTOMATICALLY obeyed

**using symmetries
of Scholler & Schon's diagrams:**

Real time diagrammatics (1994)
Whitney (2018)
see also works of M. Wegewijs



WHAT HAVE WE LEARNT SO FAR?

(1) Trapdoor always obeys 2nd law

(2) Need local detailed balance (I believe this is missing from Smoluchovski's argument)

OPEN QUESTION:

Does analysis of the quantum two-state trapdoor

help explain

the macroscopic trapdoor with beans??

ONGOING

RESEARCH & COLLABORATION

Optimizing resource efficiencies for scalable full-stack quantum computers

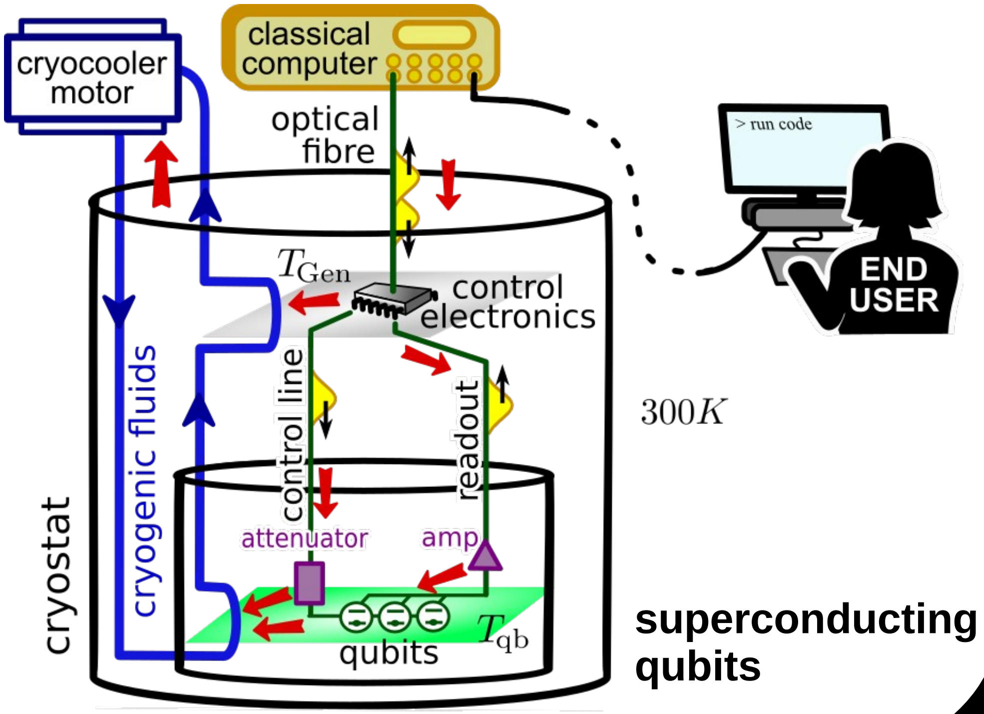
Marco Fellous-Asiani

Jing Hao Chai

Yvain Thonnart

Hui Khoon Ng

Alexia Auffèves



Noise

Metric

Resource

Konstantina Koteva

➔ spin qubits

➔ microwave cables

Team collaboration with Alexia Auffeves

Energetics of Quantum Systems

Alexia

Irénée Frérot

Maria Maffei

Patrice Camati

Nicolò Piccione

Konstantina Koteva

Weird types of decoherence

- ➔ Ultra-slow noise : spin-qubits, etc
- ➔ Intrinsic decoherence : flying qubits

Non-therrmal reservoirs

- ➔ non-equilibrium demons
- ➔ "beyond quantum thermo" (waveguides as baths)

Energy & entropy in quantum error correction

- ➔ surface codes + cat codes
- ➔ autonomous error correction

Lea Bresque

Bruno Goes

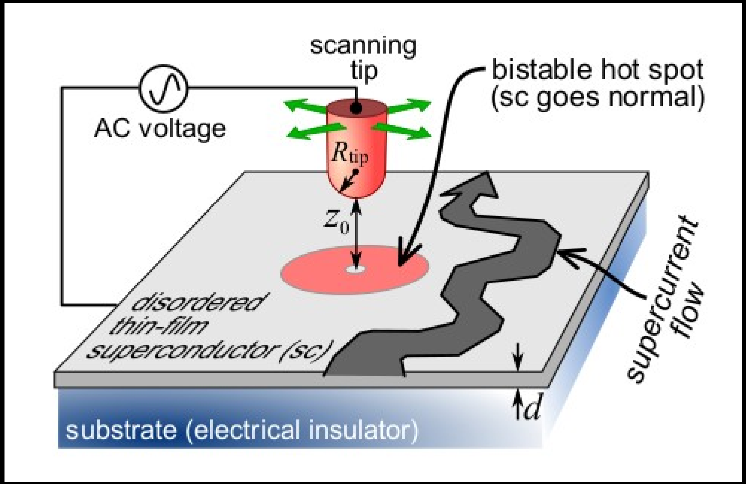
Samyak Prasad

Elisa Bossard

Team collaboration with Denis Basko, Rodolfo Jalabert, Dietmar Weinmann

Local probes of dissipation in nanoelectronics

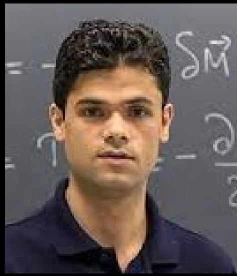
Denis Basko



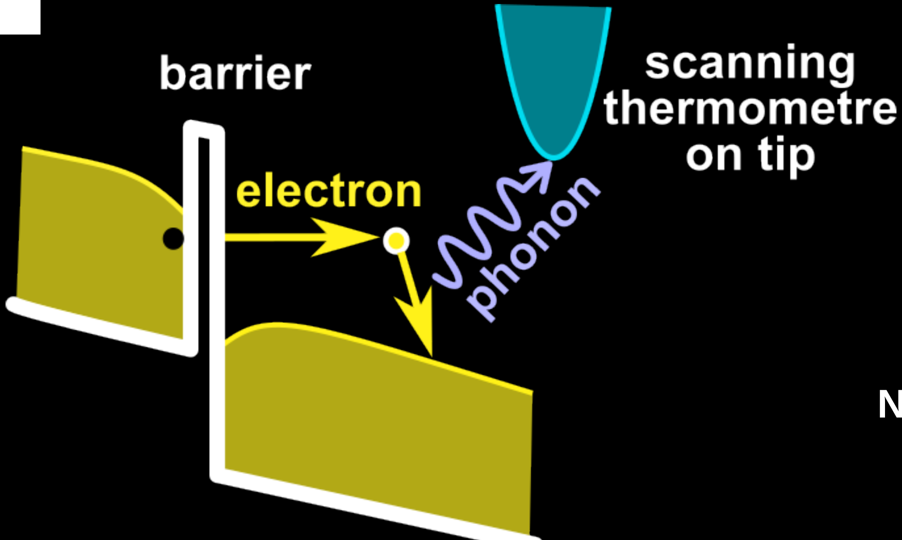
Rodolfo Jalabert

Dietmar Weinmann

local heating
of disordered
superconductor



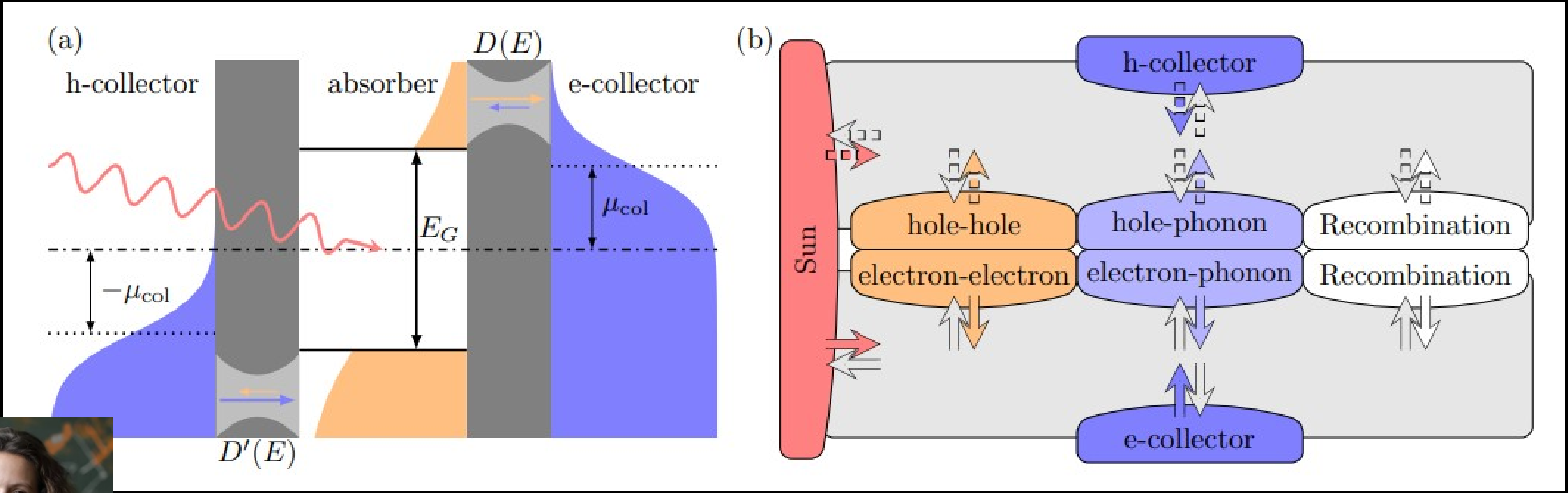
Deepak Karki



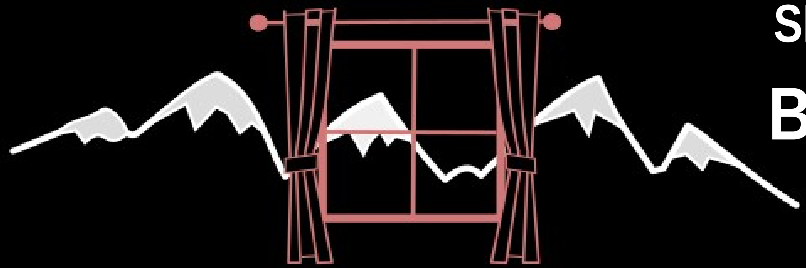
Nico Leumer

Collaboration with Janine Splettstoesser

Hot carrier photovoltaics



Janine Splettstoesser & Ludovico Tesser
(PhD 2021-2024)



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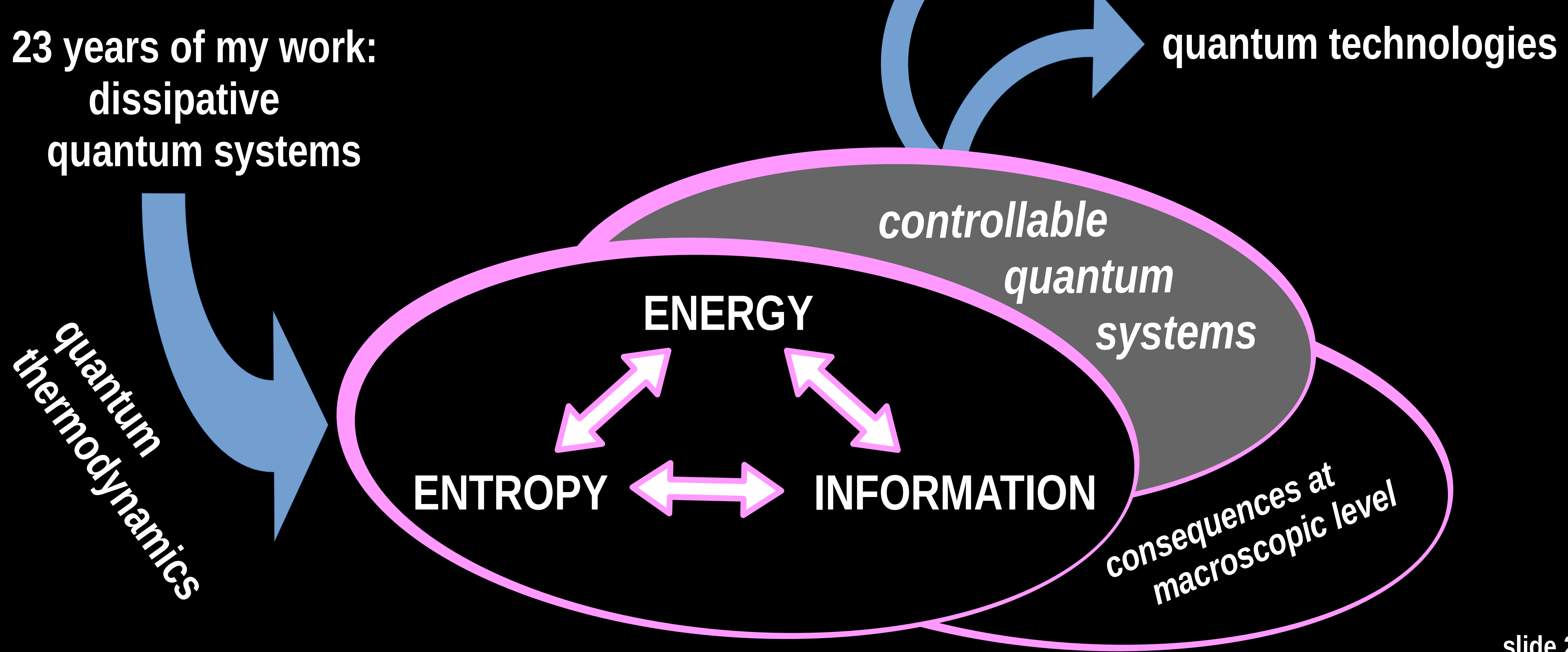
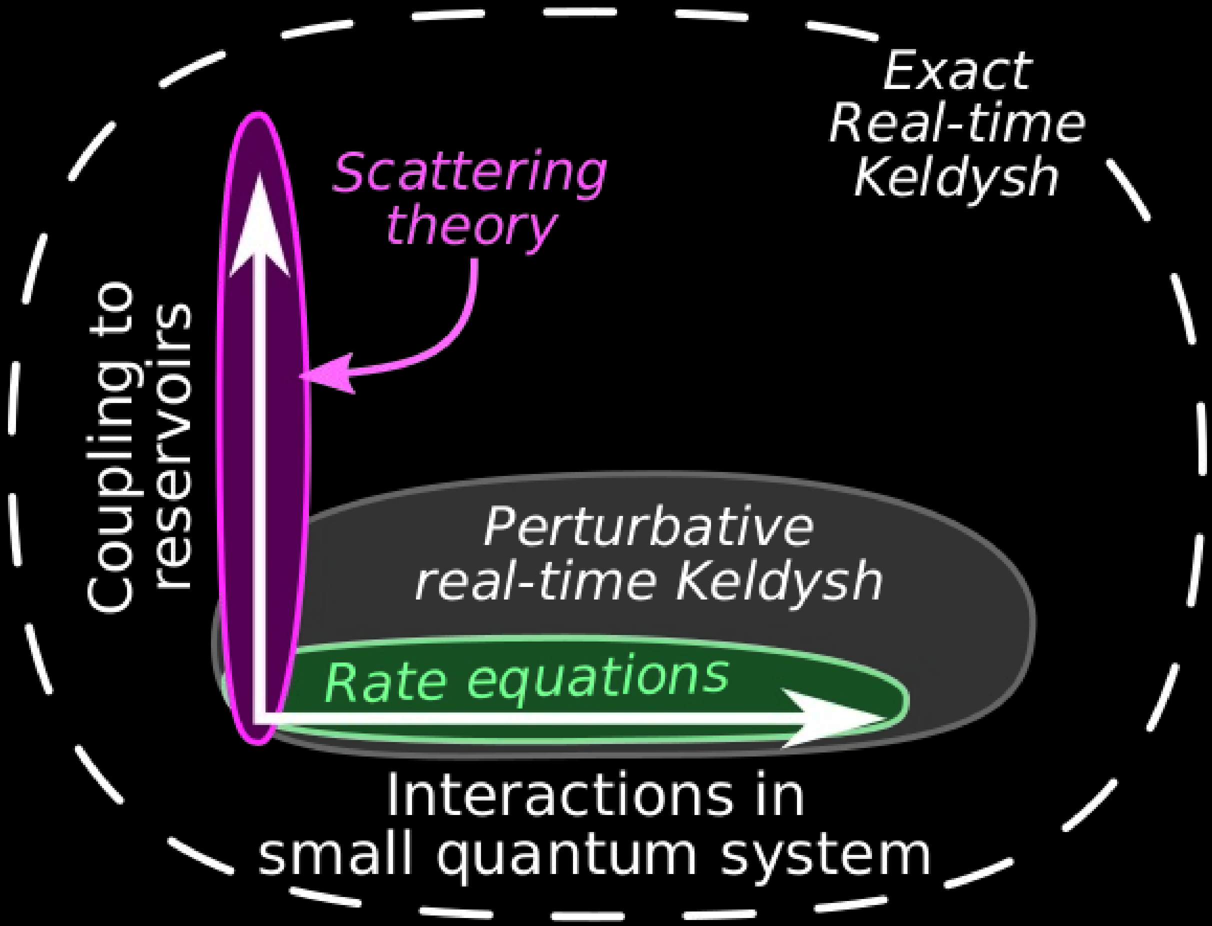
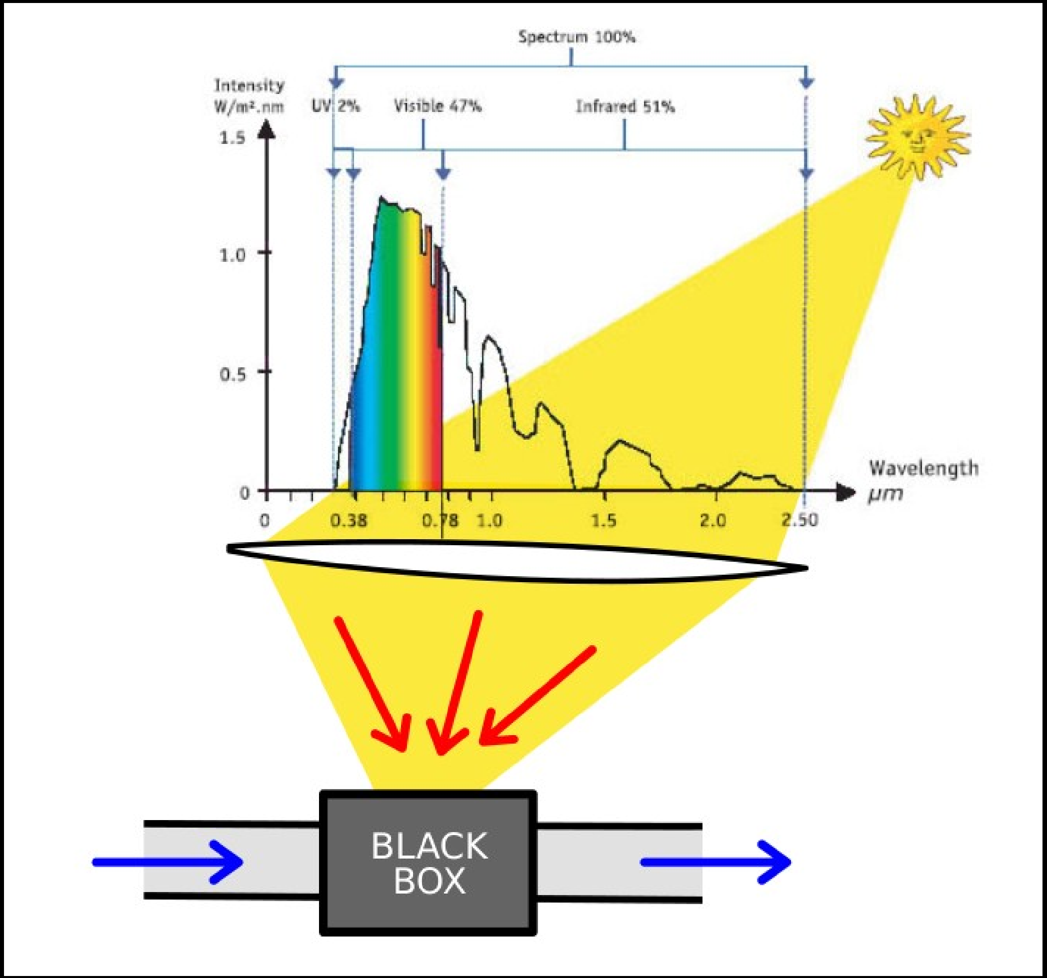
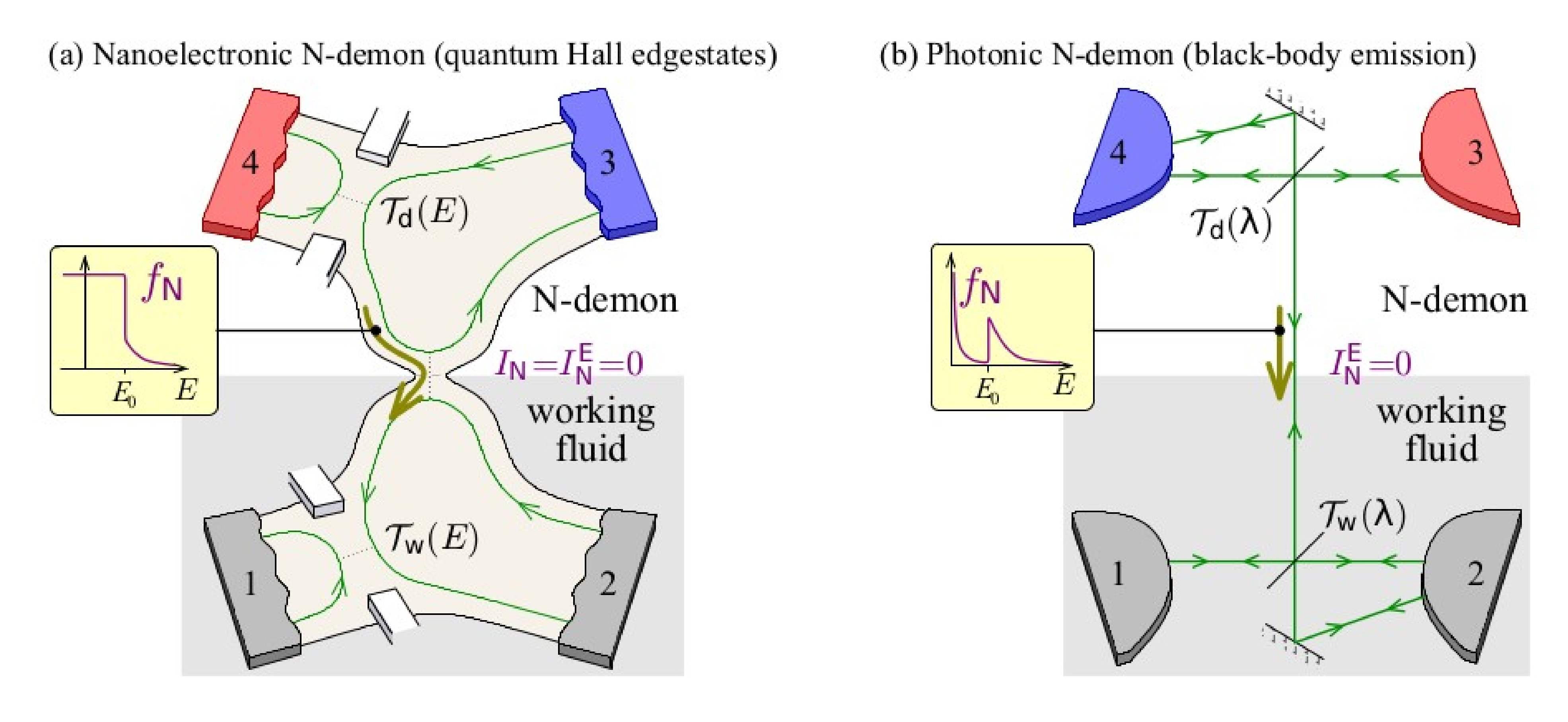


OTHER SLIDES

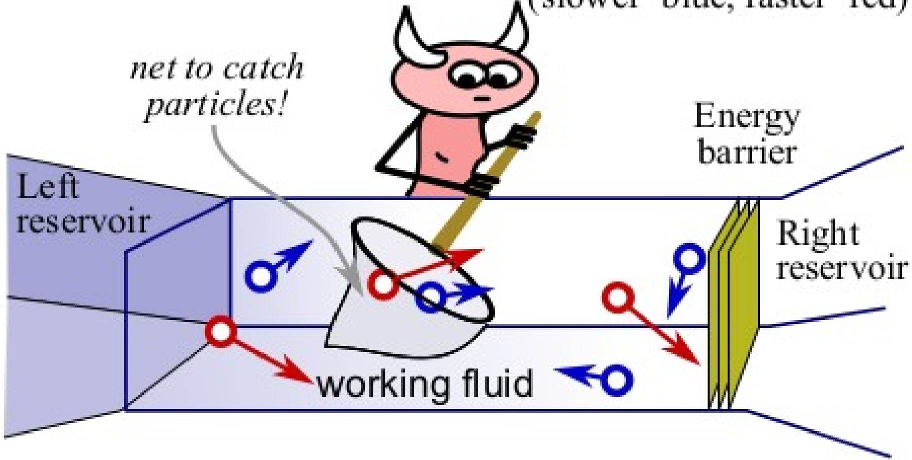
Summary of theoretical methods



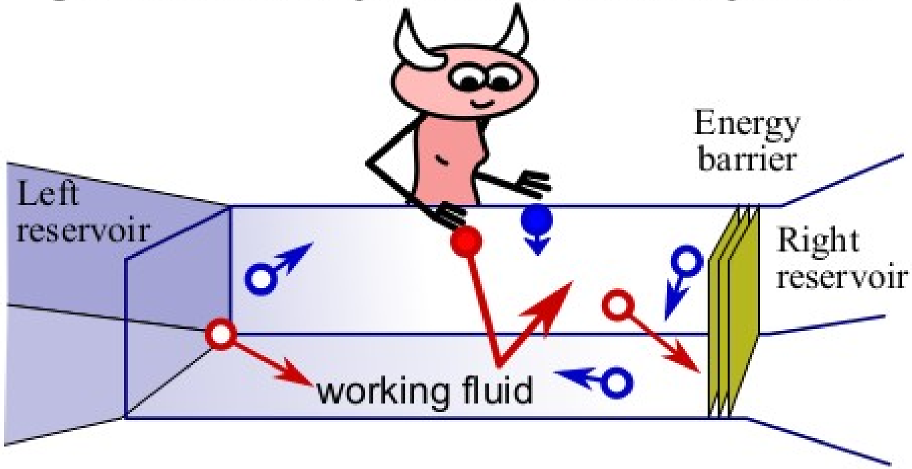

Spectrum 100%
Intensity W/m².nm
UV 2%
Visible 47%
Infrared 51%
1.5
1.0
0.5
0
0
0.38
0.78
1.0
1.5
2.0
2.50
Wavelength μm
BLACK BOX

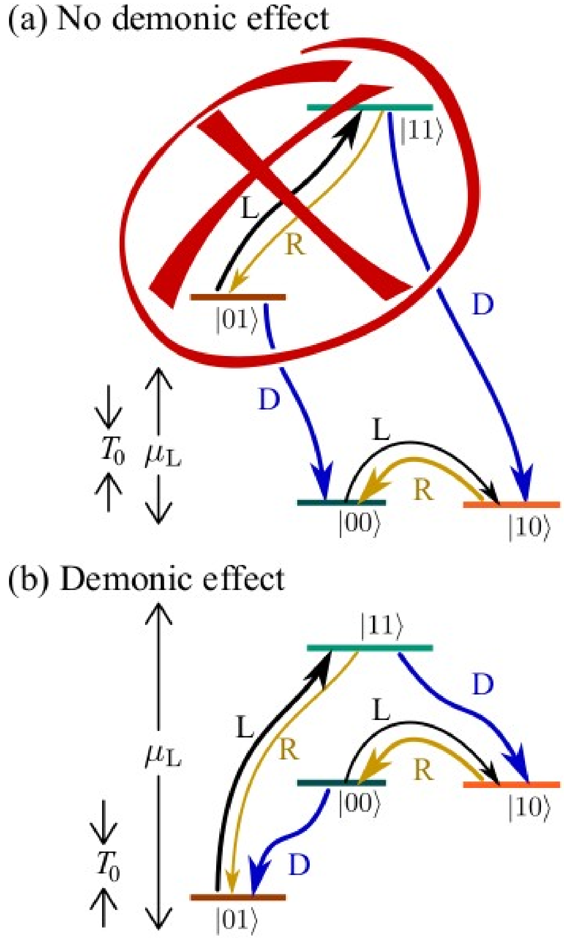

(a) Nanoelectronic N-demon (quantum Hall edgestates)
4
3
$\mathcal{T}_d(E)$
f_N
E_0
E
N-demon
$I_N = I_N^E = 0$
working
fluid
$\mathcal{T}_w(E)$
1
2
(b) Photonic N-demon (black-body emission)
4
3
$\mathcal{T}_d(\lambda)$
f_N
E_0
E
N-demon
$I_N^E = 0$
working
fluid
$\mathcal{T}_w(\lambda)$
1
2

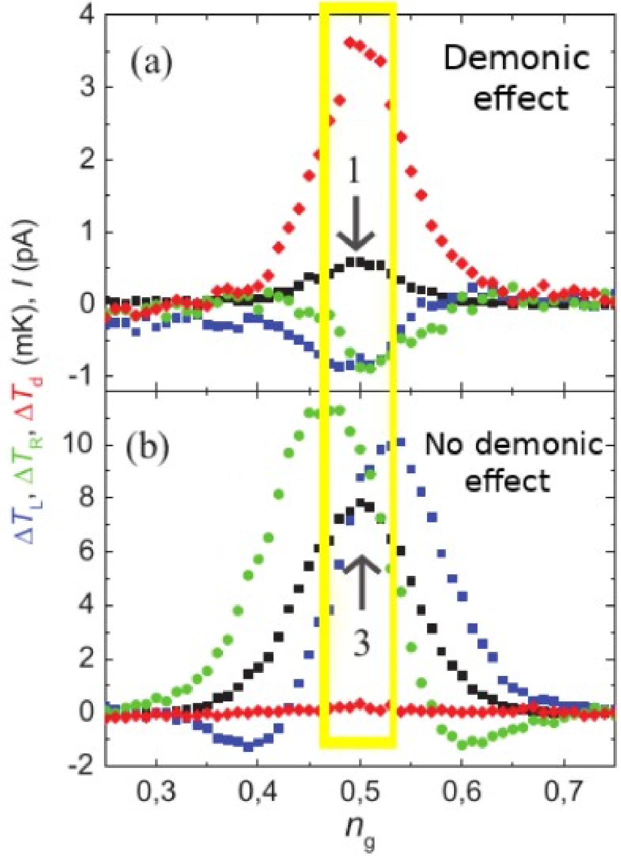
(a) The demon catches one slower and one faster particle
(slower=blue, faster=red)

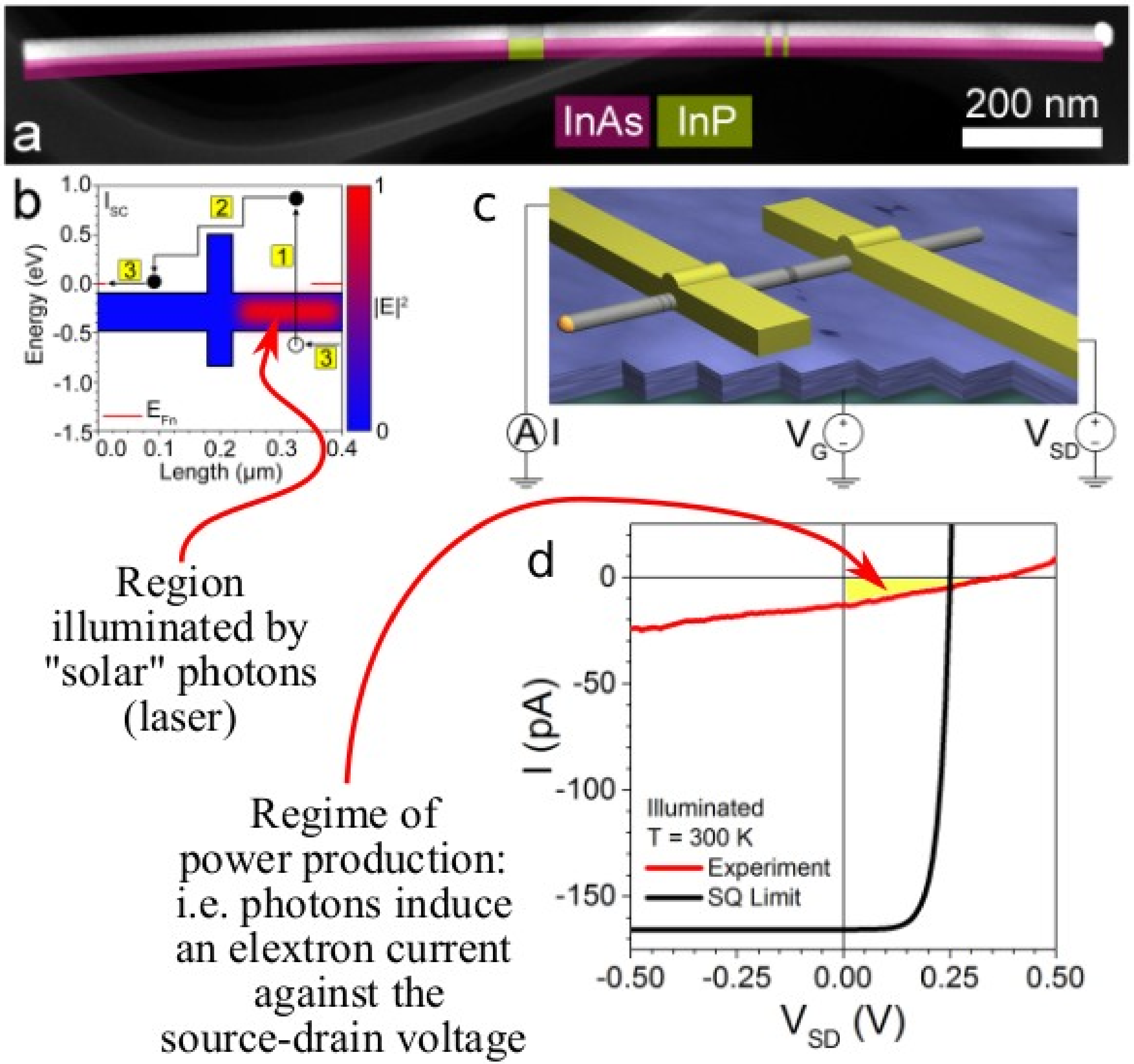


(b) The demon takes kinetic energy from the slower particle, gives it to the faster particle, & releases both particles.




(a) No demonic effect
|11⟩
L
R
D
|01⟩
D
T0
μL
L
R
|00⟩
|10⟩
(b) Demonic effect
|11⟩
L
R
D
L
R
μL
|00⟩
|10⟩
D
T0
|01⟩


(a)
Demonic effect
1
(b)
No demonic effect
3
ΔTL, ΔTR, ΔTd (mK), I (pA)
ng
0,3
0,4
0,5
0,6
0,7


a
InAs
InP
200 nm
b
Energy (eV)
Length (µm)
I_{sc}
$|E|^2$
E_{Fn}
c
I
V_G
V_{SD}
d
I (pA)
V_{SD} (V)
Illuminated
T = 300 K
Experiment
SQ Limit
Region illuminated by "solar" photons (laser)
Regime of power production: i.e. photons induce an elextron current against the source-drain voltage