Thermal machines at the single trajectory level & stochastic excursions

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III Workshop on Quantum Information and Quantum Thermodynamics
Rio

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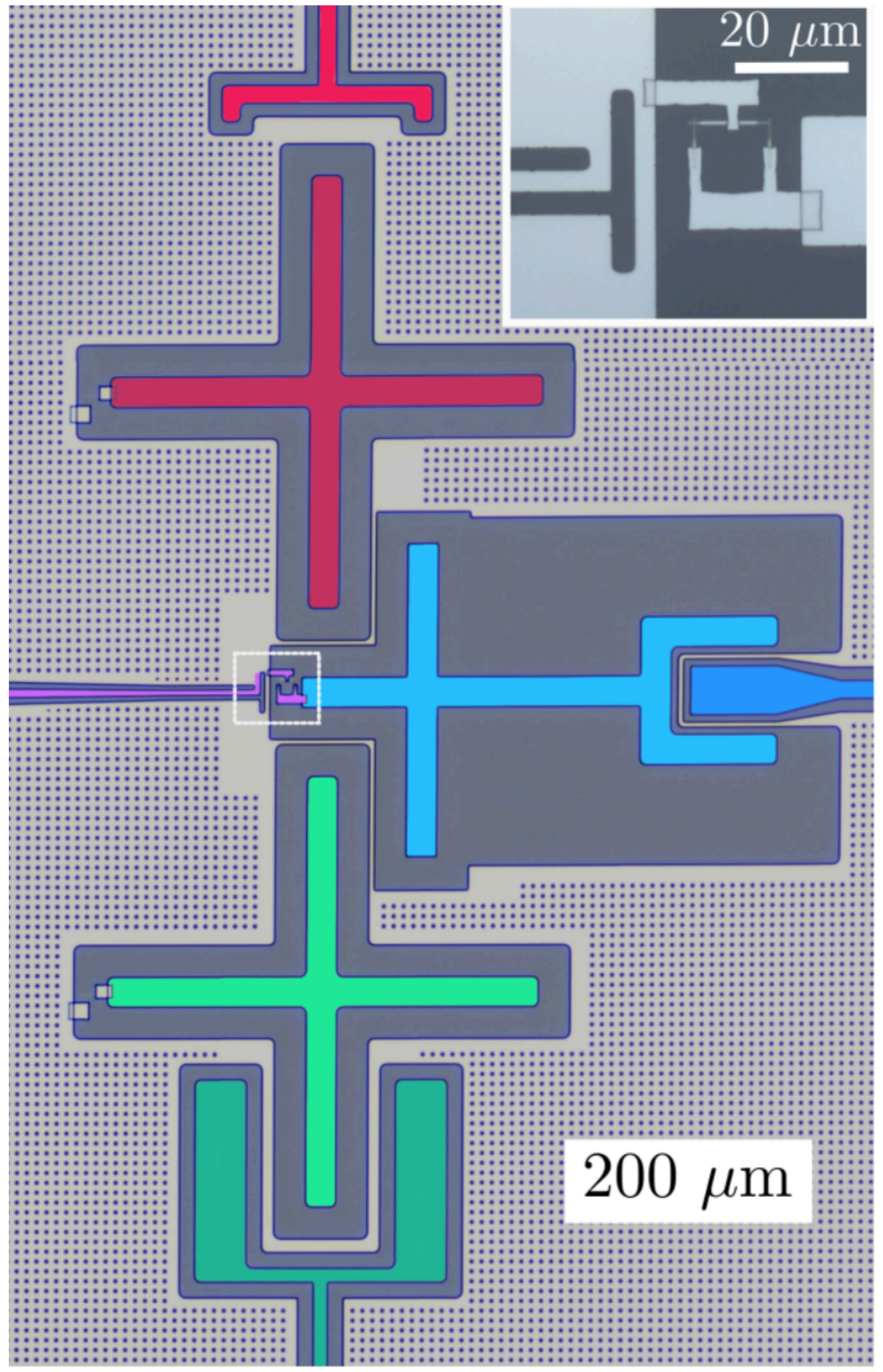
Cooling on-demand

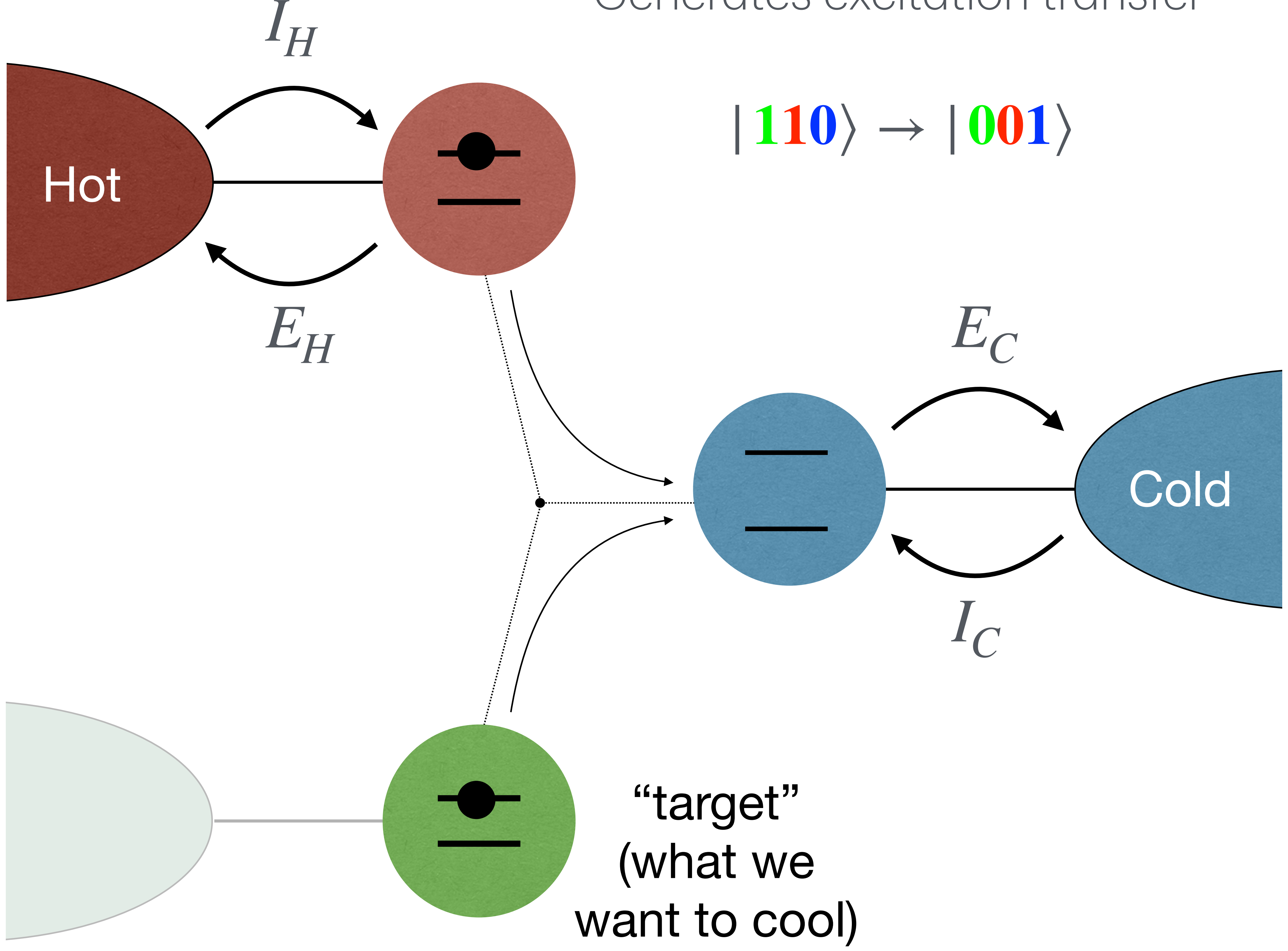
3-body resonant interaction

$$\omega_h + \omega_t = \omega_c$$

Generates excitation transfer

$$|110\rangle \rightarrow |001\rangle$$





Steady-state picture: currents J_H and J_C

On-demand picture: If an excitation suddenly appears in green, extract it as fast as possible.

Changes the questions:

- How long does it take to cool?
- How many things can go wrong before it works?
- What is the entropy production of a single cooling event?

Aamir, M. A. et al. “**Thermally driven quantum refrigerator autonomously resets superconducting qubit”** arXiv.2305.16710 (2023).

Cooling on-demand

3-body resonant interaction

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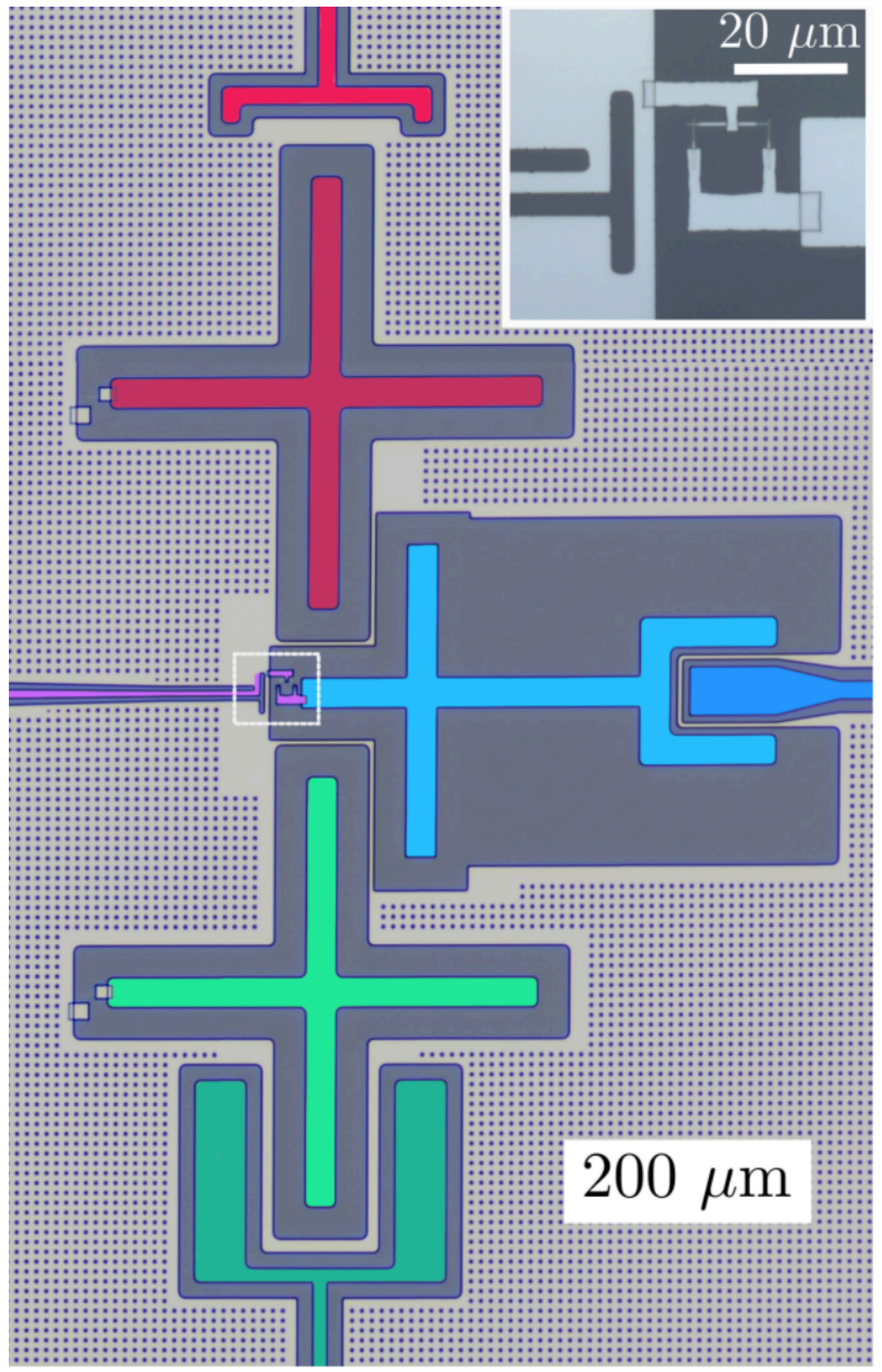
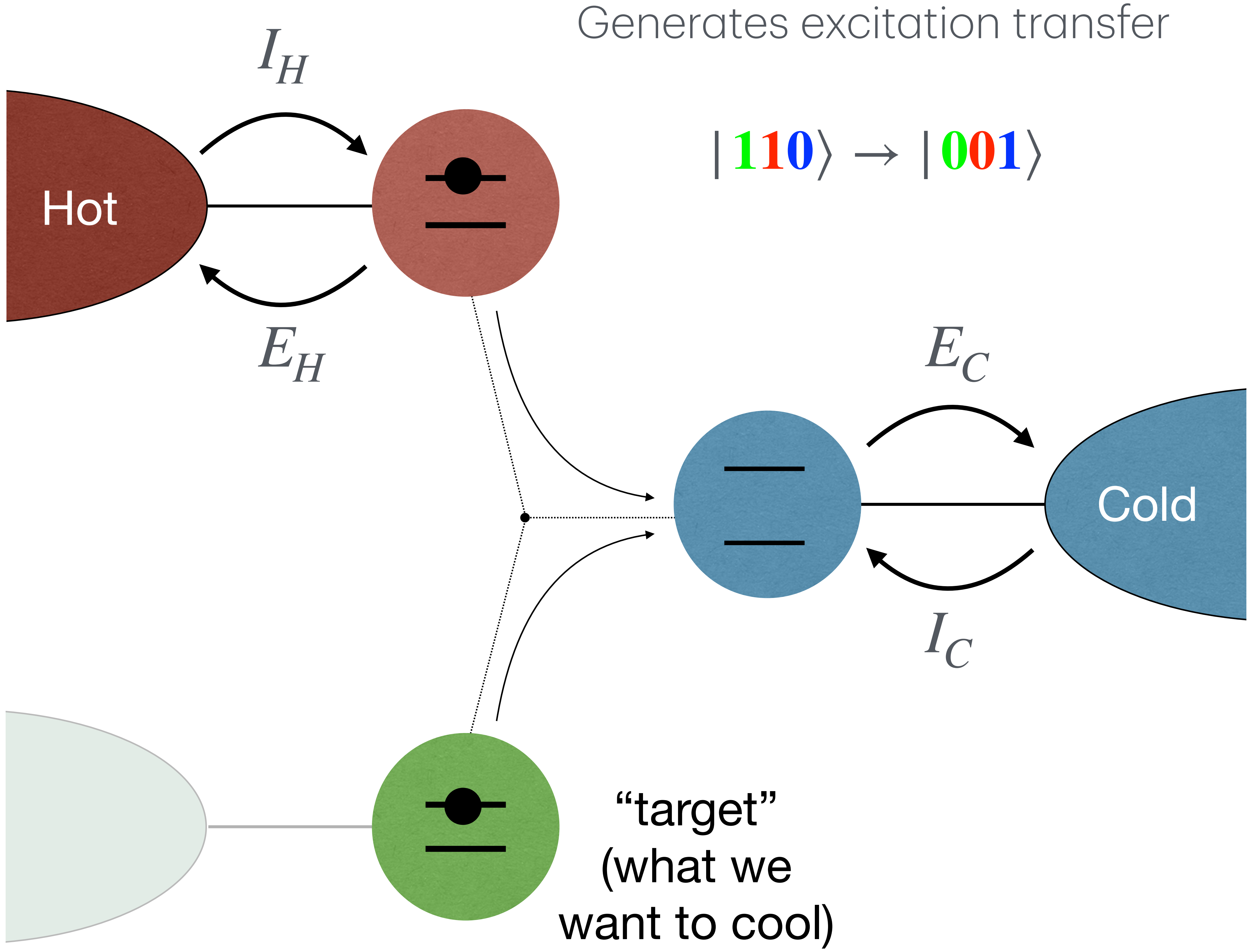
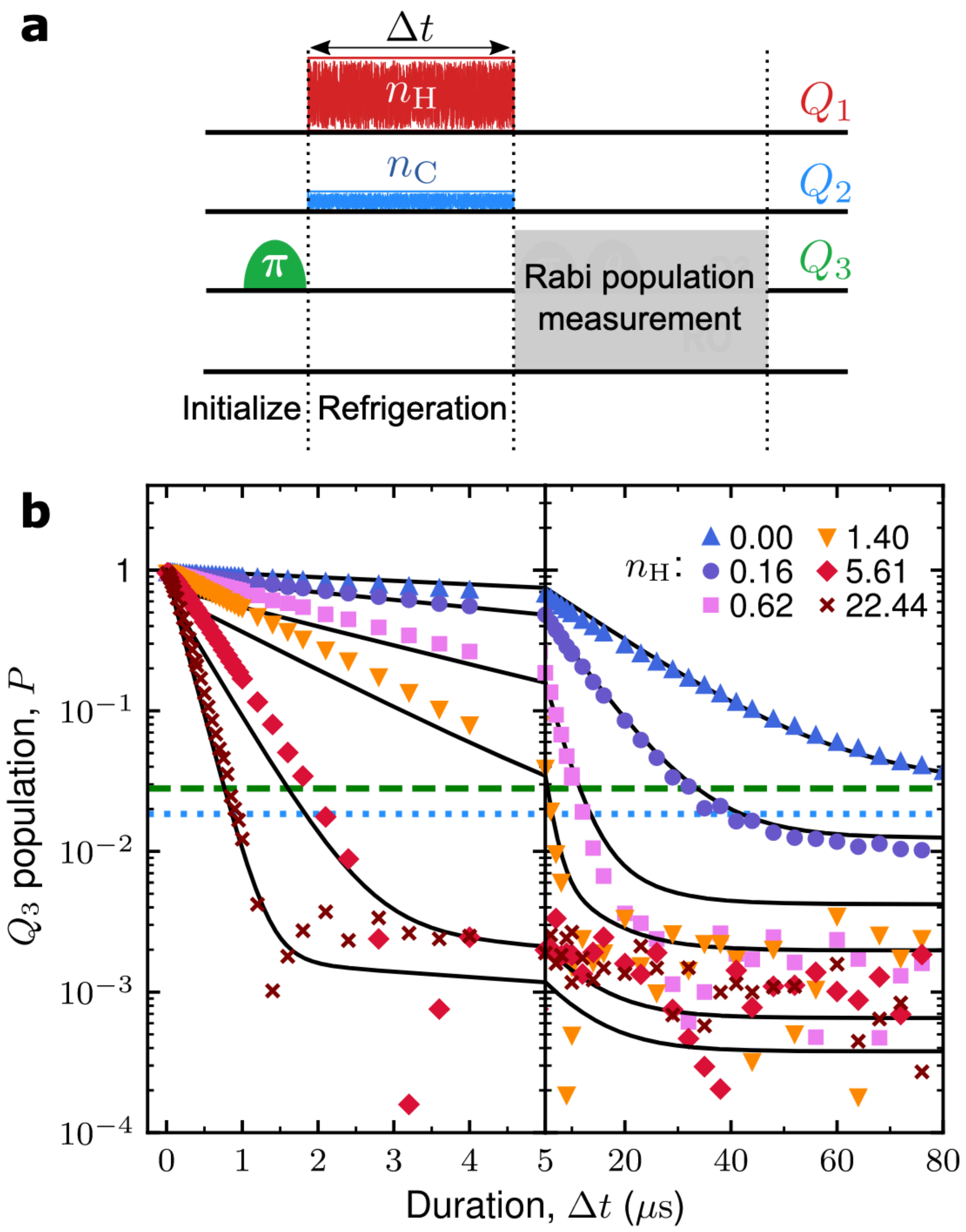






Aamir, M. A. et al. "**Thermally driven quantum refrigerator autonomously resets superconducting qubit**" arXiv.2305.16710 (2023).

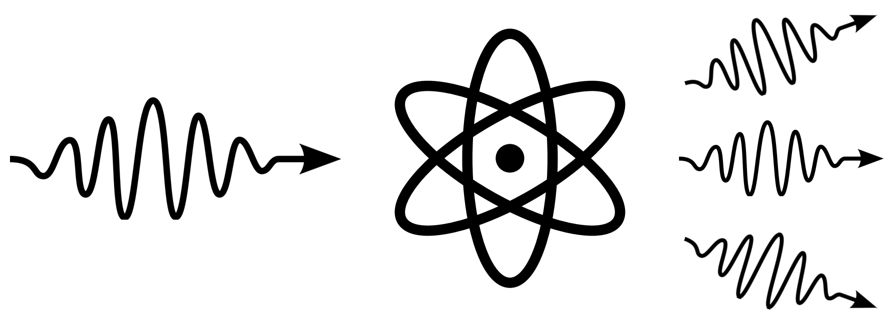
What is stochastic quantum thermodynamics?

We cannot see quantum systems…

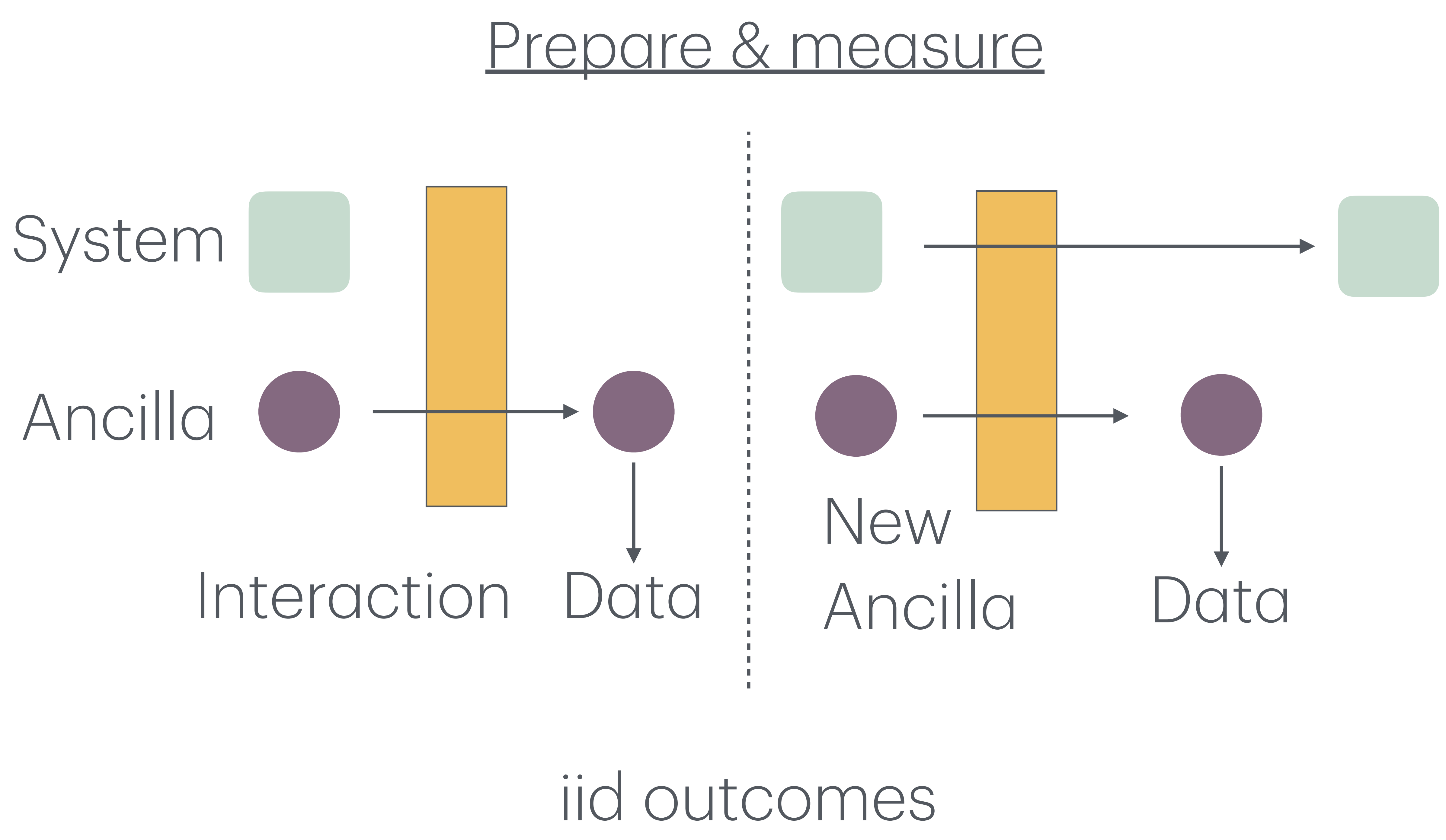
All we see is data …11100001000100111001111101100…

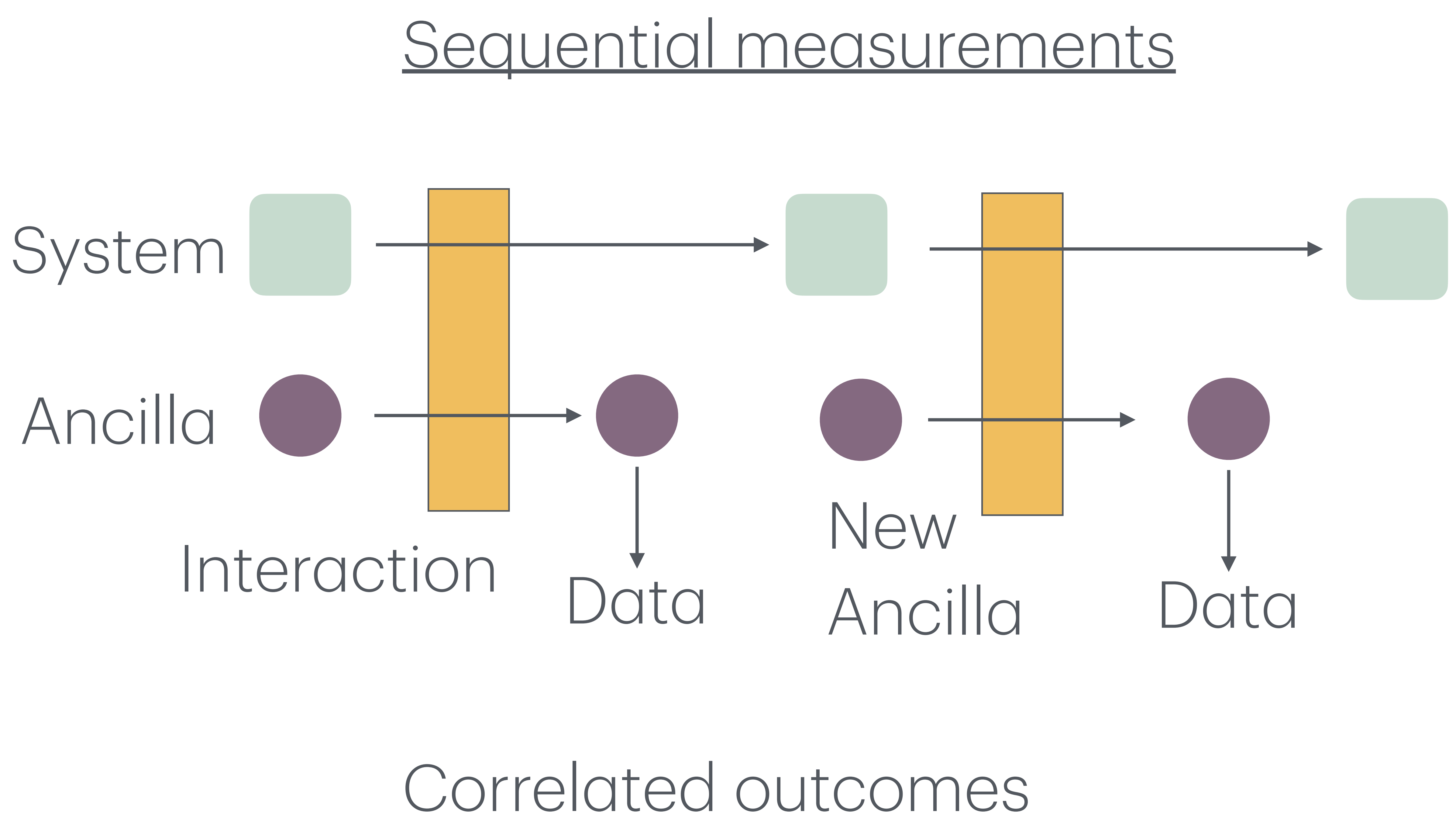
How can we study the stochastic thermodynamics of quantum devices?

- To measure a system we must send in a **probe** (or **ancilla**).
  - S+A interaction encodes information about S on A.
  - Extract information by measuring A.



- **Information-back action trade-off:** the more information we want, the more we disturb the system.





A simple example

- Qubit: apply unitary U then measure in the computational basis $P_x = |x\rangle\langle x|$ where $x = 0,1$.
- Start in $|\psi_0\rangle$.

  1. Sample first outcome x_1 from $p(x_1) = |\langle x_1|U|\psi_0\rangle|^2$.
     Update state to $|\psi_1\rangle = |x_1\rangle$.

  2. Sample second outcome x_2 from $p(x_2|x_1) = |\langle x_2|U|x_1\rangle|^2$.
     Update state to $|\psi_2\rangle = |x_2\rangle$.

- Generates a **bitstring of emitted symbols** $x_{1:n} = (x_1, \ldots, x_n)$.
- Probability of a sequence forms a Markov chain: $P(x_1, \ldots, x_n) = p(x_n|x_{n-1})\ldots p(x_2|x_1)p(x_1)$.

Non-projective measurements lead to long memory

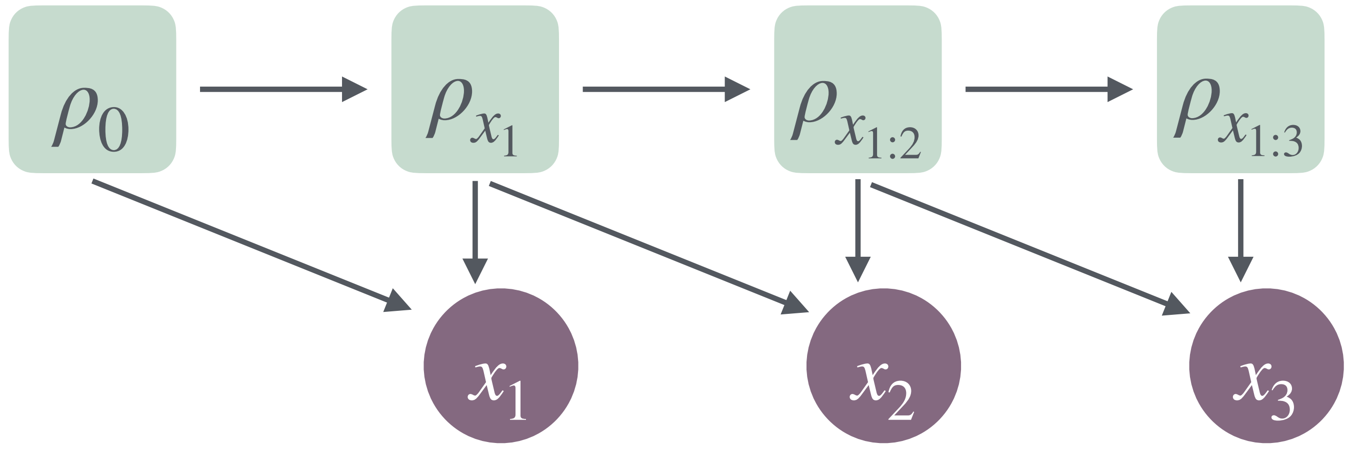
- Apply a set of Kraus operators $\sum_x F_x^\dagger F_x = 1$. Starting at ρ_0:

  1. Sample first outcome x_1 from $p(x_1) = \mathrm{tr}\{F_{x_1}\rho_0 F_{x_1}^\dagger\}$. Update state to $\rho_{x_1} = \dfrac{F_{x_1}\rho_0 F_{x_1}^\dagger}{p(x_1)}$.

  2. Sample second outcome x_2 from $p(x_2|x_1) = \mathrm{tr}\{F_{x_2}\rho_{x_1} F_{x_2}^\dagger\}$. Update state to $\rho_{x_{1:2}} = \dfrac{F_{x_2}\rho_{x_1} F_{x_2}^\dagger}{p(x_2|x_1)}$.

$$p(x_{n+1}|x_{1:n}) = \mathrm{tr}\left\{F_{x_{n+1}}\rho_{x_{1:n}} F_{x_{n+1}}^\dagger\right\} \quad \text{and} \quad \rho_{x_{1:n+1}} = \frac{F_{x_{n+1}}\rho_{x_{1:n}} F_{x_{n+1}}^\dagger}{p(x_{n+1}|x_{1:n})}$$

- String probability is now $P(x_{1:n}) = p(x_n|x_{1:n-1})p(x_{n-1}|x_{1:n-2})\dots p(x_2|x_1)p(x_1)$ which is highly non-Markovian.
  - *Evolution of the system is Markovian. But output data is not.*
- Looks like a Hidden Markov Model (HMM):
  - Quantum system is hidden.
  - Measurement outcomes (what we see) = **emitted symbols**



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GTL "**Patterns in the jump-channel statistics of open quantum systems**," arXiv 2305.07957

Instruments: simplify and generalize

- Instruments = superoperators:

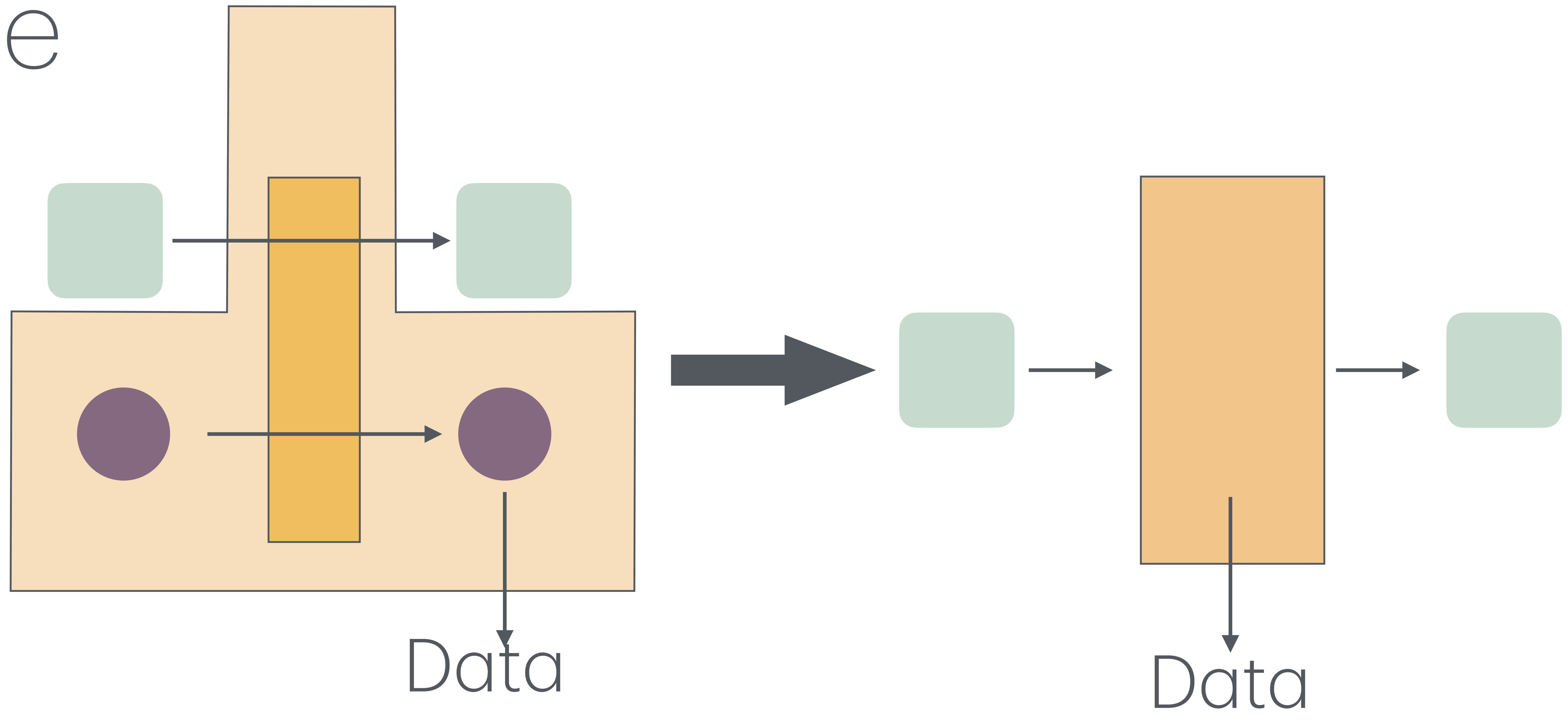
$$M_x\rho = F_x\rho F_x^\dagger$$

- Update rules become:

$$p(x_{n+1} \,|\, x_{1:n}) = \mathrm{tr}\left\{M_{x_{n+1}}\rho_{x_{1:n}}\right\}$$

and

$$\rho_{x_{1:n+1}} = \frac{M_{x_{n+1}}\rho_{x_{1:n}}}{p(x_{n+1} \,|\, x_{1:n})}$$



Prob. of a string:

$$P(x_{1:n}) = \mathrm{tr}\left\{M_{x_N}\ldots M_{x_1}\rho_0\right\}$$

Conditional state

$$\rho_{x_{1:n}} = M_{x_N}\ldots M_{x_1}\rho_0/P(x_{1:n})$$

Instruments represent the most general kind of measurement possible.

Also encompass inefficient measurements

$$M_x\rho = \sum_{k\in x} F_k\rho F_k^\dagger$$

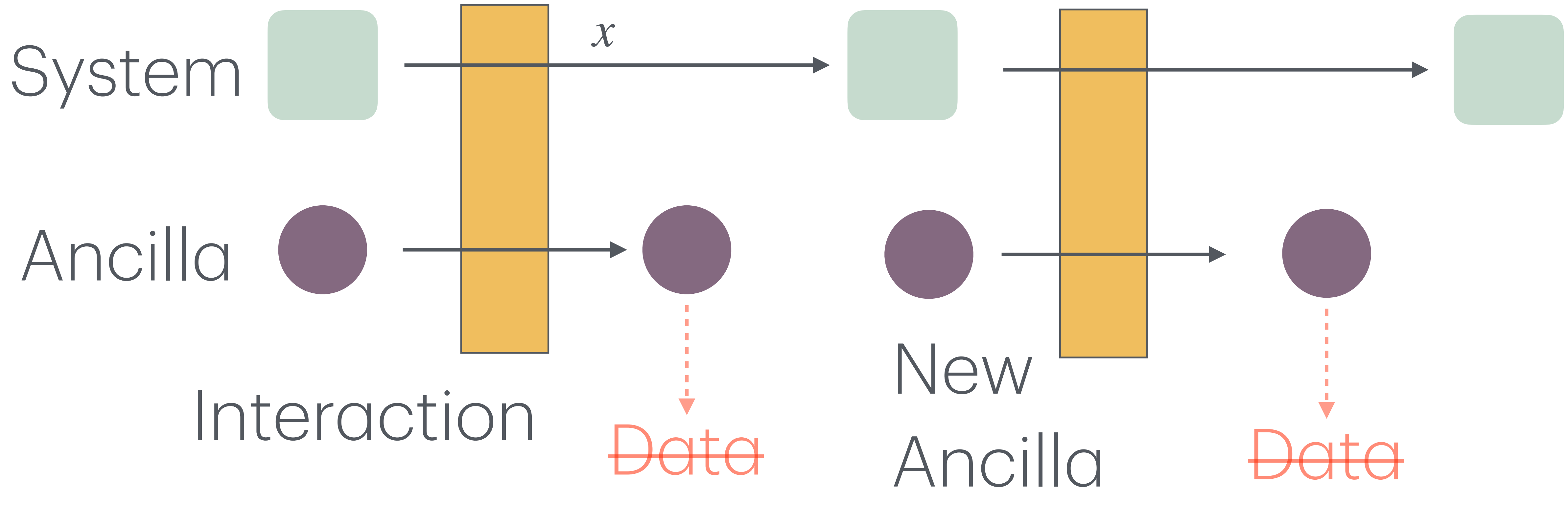
Wiseman, H. M. & Milburn, G. J. **Quantum Measurement and Control.** (Cambridge University Press, New York, 2009)

Unconditional dynamics

- If we measure but don't record the outcome the state of the system still changes (measurement back action)

- Ex: collision model or master equation.

$$\rho' = \sum_x p_x \rho'_x = \sum_x M_x \rho = \mathscr{M}\rho \qquad \text{where} \qquad \mathscr{M} = \sum_x M_x$$

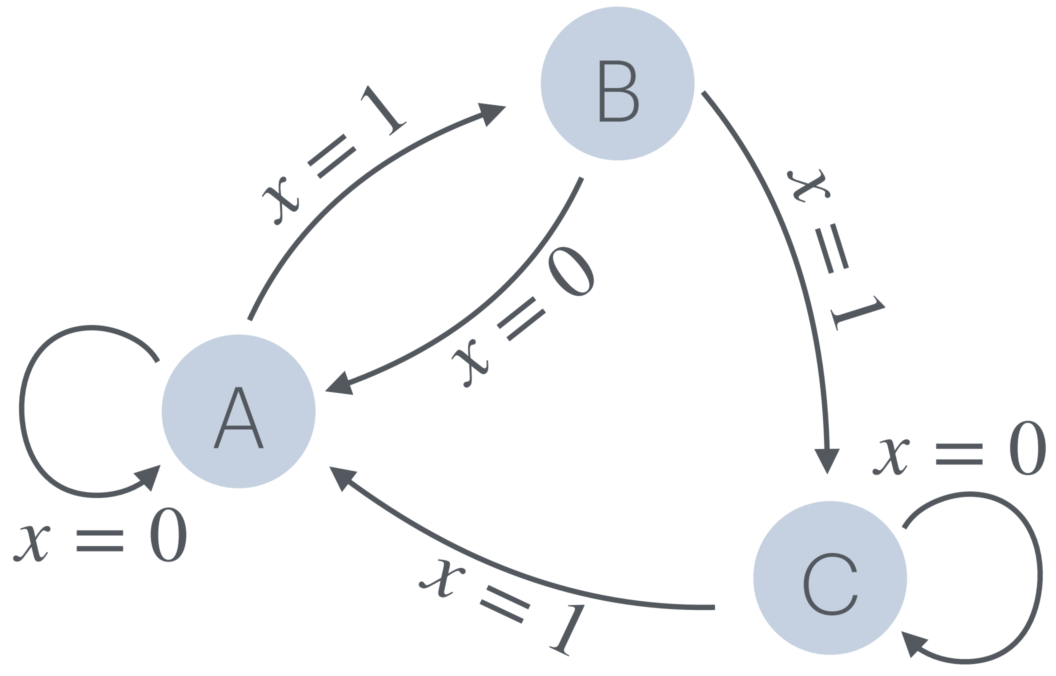


- $\mathscr{M}$ is a quantum channel.

- After n steps: $\rho_n = \mathscr{M}^n \rho_0$.

- Describes the average impact that the interaction with the ancilla causes in the system.

Connection to Hidden Markov Models



- $P(x, \sigma \,|\, \sigma')$ = prob. that system goes from $\sigma' \to \sigma$ while emitting a symbol x.
  - If HMM state is $\pi(\sigma')$ the prob. that we observe symbol x is

$$p(x) = \sum_{\sigma,\sigma'} P(x, \sigma \,|\, \sigma')\pi(\sigma')$$

- If outcome was x, bayesian update the state of the hidden layer:

$$\pi(\sigma \,|\, x) = \frac{P(x, \sigma)}{p(x)} = \frac{\sum_{\sigma'} P(x, \sigma \,|\, \sigma')\pi(\sigma')}{p(x)}$$

- Define substochastic matrices: $(M_x)_{\sigma,\sigma'} = P(x, \sigma \,|\, \sigma')$ and $\langle 1 \,| = (1,\ldots,1)$. Then

$$p(x) = \langle 1 \,|\, M_x \,|\, \pi \rangle \qquad \text{and} \qquad |\, \pi_x \rangle = \frac{M_x \,|\, \pi \rangle}{p(x)}$$

Compare with

$$p(x) = \mathrm{tr}\{M_x \rho\}$$

and

$$\rho_x = \frac{M_x \rho}{p(x)}$$

Milz, S. & Modi, K. "**Quantum Stochastic Processes and Quantum non-Markovian Phenomena**". PRX Quantum 2, 030201 (2021)

Prediction

- **Mixed state representation & unifilar models:** if we know $\rho_{x_{1:n}}$ and we observe x_{n+1} we know with certainty that the system evolved to $\rho_{x_{1:n+1}}$.

- Usefulness: data compression

$$p(x_{n+1} | x_{1:n}) = p(x_{n+1} | \rho_{x_{1:n}})$$

If we can know the internal state, we can make statistical predictions of future outcomes.

- Example: figuring out the internal state of a large language model.

F. Binder, J. Thompson, M. Gu, "**Practical unitary simulator for non-Markovian complex processes**," *Phys. Rev. Lett.* **120** 240502 (2018).

Quantum jumps

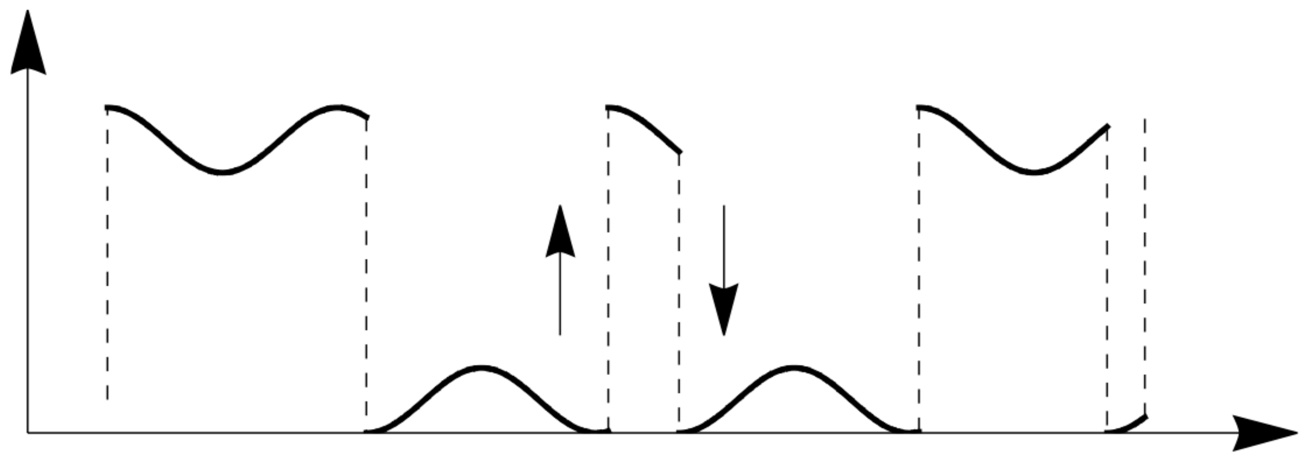
Mark Mitchison

Michael Kewming

Patrick Potts

GTL, Michael J. Kewming, Mark T. Mitchison, Patrick P. Potts **"Current fluctuations in open quantum systems: Bridging the gap between quantum continuous measurements and full counting statistics,"** PRX Quantum 5, 020201 (2024)

GTL "**Patterns in the jump-channel statistics of open quantum systems**," arXiv 2305.07957



- Consider a quantum master equation

$$\frac{d\rho}{dt} = \mathscr{L}\rho = -i[H,\rho] + \sum_{x=1}^{r} L_x \rho L_x^\dagger - \frac{1}{2}\{L_x^\dagger L_x, \rho\}$$

- The infinitesimal evolution can be written as a set of instruments:

$$\rho_{t+dt} = e^{\mathscr{L}dt}\rho_t = \sum_x M_x \rho_t$$

(jump) $\qquad M_x\rho = dt\; L_x \rho L_x^\dagger = dt\; \mathscr{J}_x \rho \qquad$ for $\qquad x = 1,2,\ldots,r$

(no jump) $\qquad M_0\rho = \rho + dt\mathscr{L}_0\rho \qquad$ where $\qquad \mathscr{L}_0\rho = -i[H,\rho] - \dfrac{1}{2}\displaystyle\sum_{x=1}^{r}\{L_x^\dagger L_x, \rho\}$

- $p_x = \mathrm{tr}\{M_x\rho\} = dt\mathrm{tr}\{L_x^\dagger L_x \rho\}$ is infinitesimal: most of the time the system evolves with no jump.

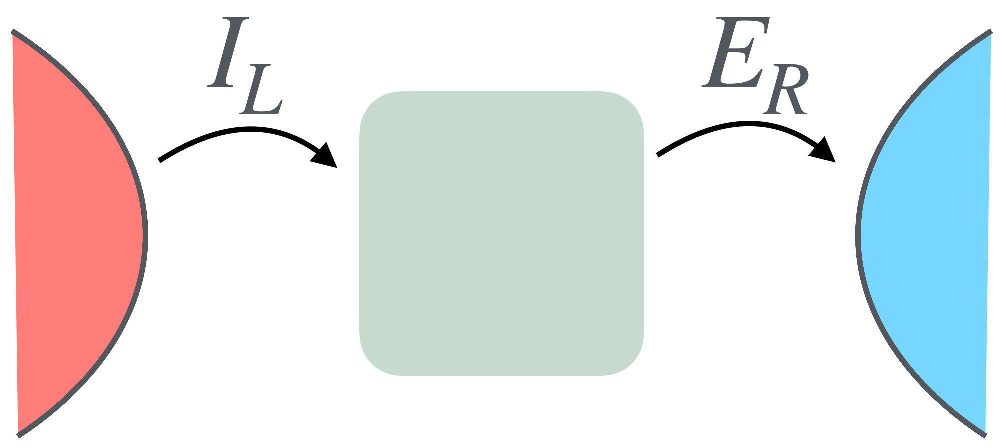
GTL, Michael J. Kewming, Mark T. Mitchison, Patrick P. Potts **"Current fluctuations in open quantum systems: Bridging the gap between quantum continuous measurements and full counting statistics,"** PRX Quantum 5, 020201 (2024)

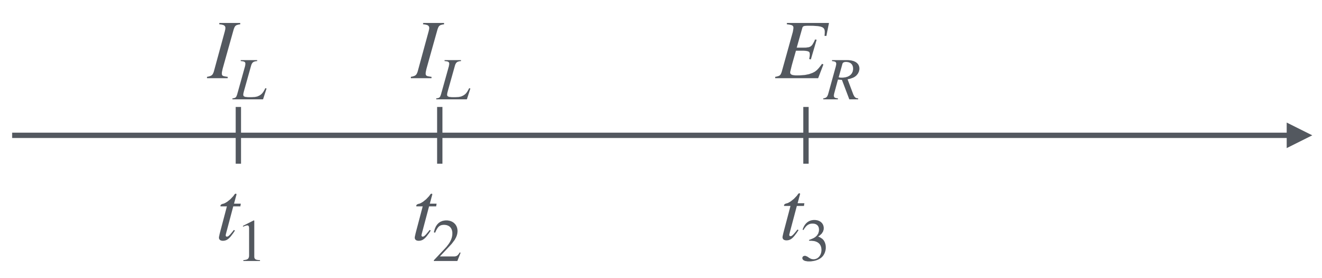
The t and the N ensembles

- **t-ensemble:** t_f fixed. $\hat{N}$ is random.
  - Instruments: $M_0\rho = (1 + dt\mathscr{L}_0)\rho$ and $M_x\rho = dt\ L_x\rho L_x^\dagger$ for $x = 1,2,\ldots r$
  - Trajectory:$00000x_1 00000000 x_2 00000\ldots$
- **N-ensemble:** N is fixed. $\hat{t}_f$ is random.
  - Instruments: $M_{x,\tau}\rho = \mathscr{J}_x e^{\mathscr{L}_0\tau}\rho$
  - Trajectory: $(x_1, \tau_1), (x_2, \tau_2), \ldots, (x_N, \tau_N)$ $\qquad \tau_j = t_j - t_{j-1}$
- Quantum jumps without time tags: we know a jump happened, but do not know when
  - Instruments: $M_x = -\mathscr{J}_x\mathscr{L}_0^{-1}$.
  - Trajectory: $x_1, x_2, \ldots$

A. A. Budini, R. M. Turner, and J. P. Garrahan. "**Fluctuating Observation Time Ensembles in the Thermodynamics of Trajectories**." Journal of Statistical Mechanics: Theory and Experiment 2014 (3): P03012 (2014)

Quantum jumps without time tags





- Lattice with L sites, each of which can have 0 or 1 particles.
  - excitations can be injected on the left (I_L)
  - or extracted on the right (E_R).
  - And they can tunnel back and forth through the chain: not monitorable.

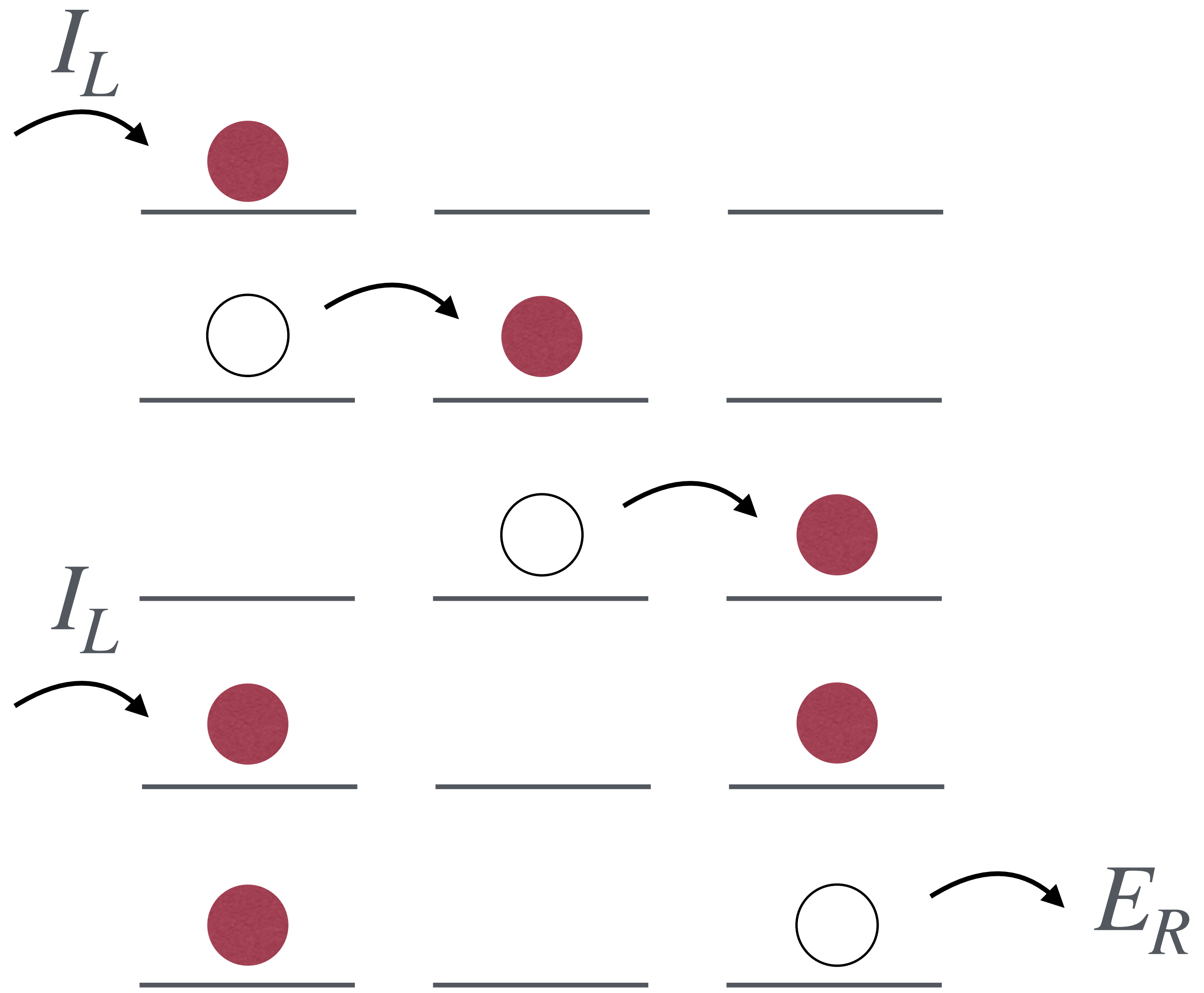
- All we would observe are symbols: $I_L I_L E_R$.

Prob. of a string:

$$P(x_{1:n}) = \mathrm{tr}\{M_{x_N} \ldots M_{x_1} \rho_0\}$$

Conditional state

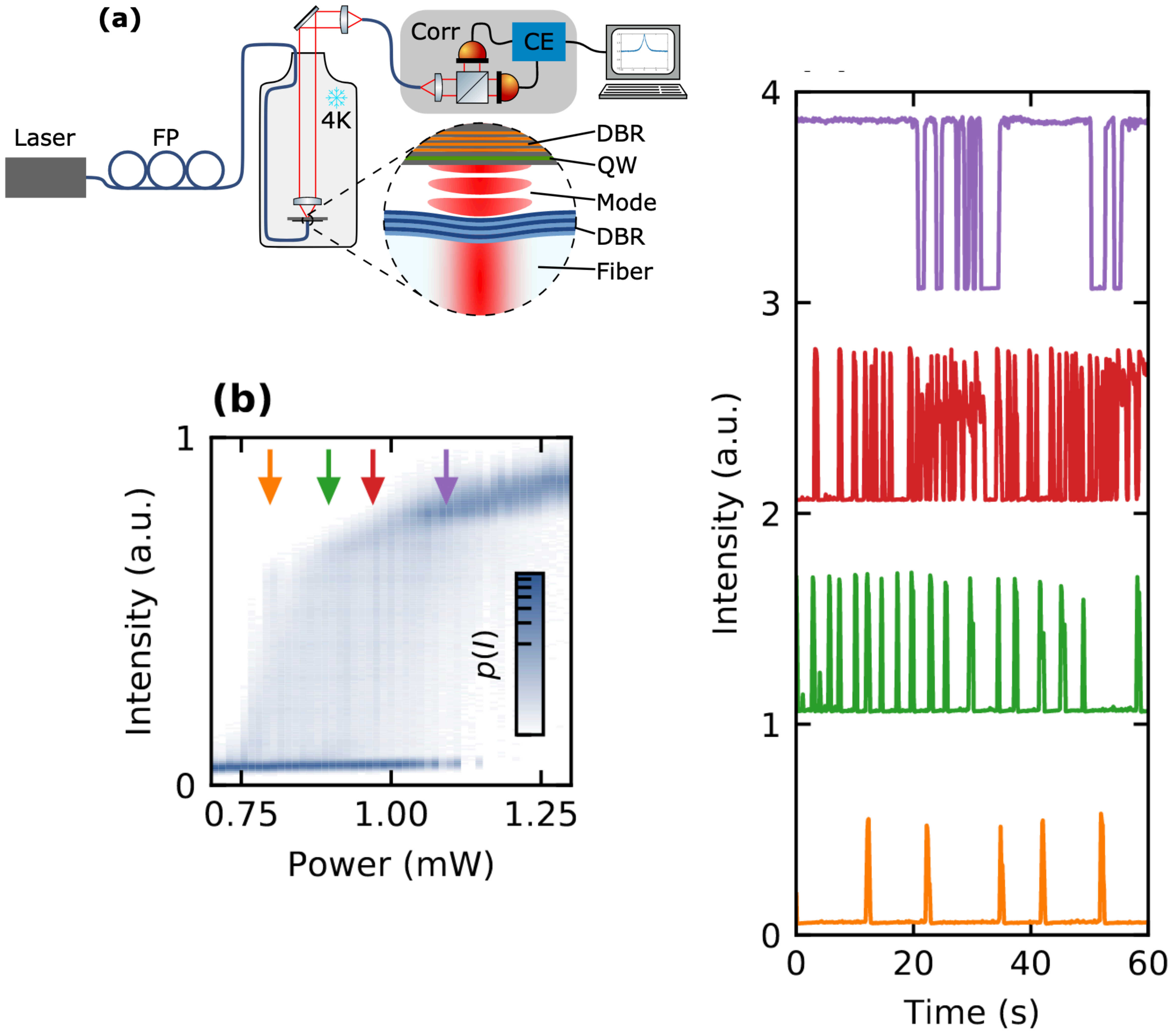
$$\rho_{x_{1:n}} = M_{x_N} \ldots M_{x_1} \rho_0 / P(x_{1:n})$$



GTL "**Patterns in the jump-channel statistics of open quantum systems**," arXiv 2305.07957

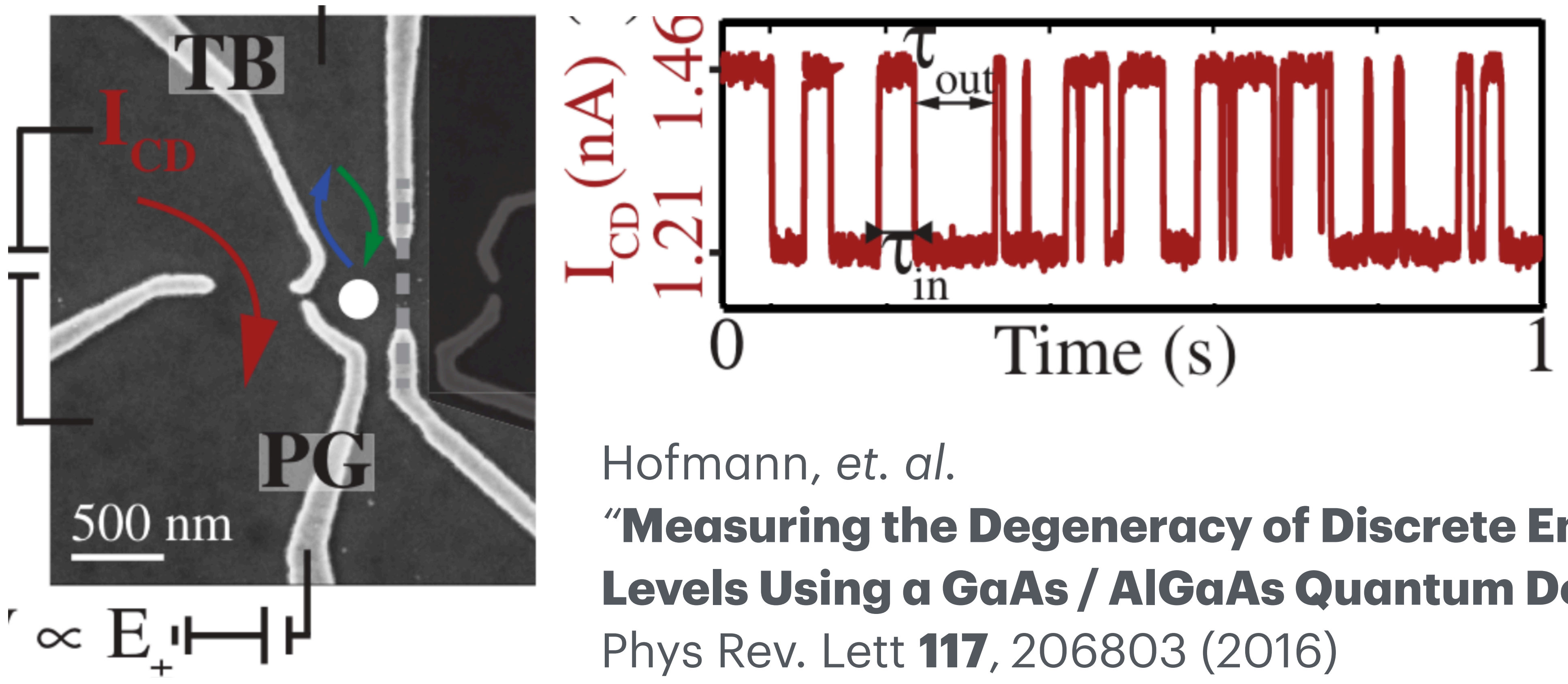
Direct and indirect observation of quantum jumps

Quantum jumps = observable clicks in the environment



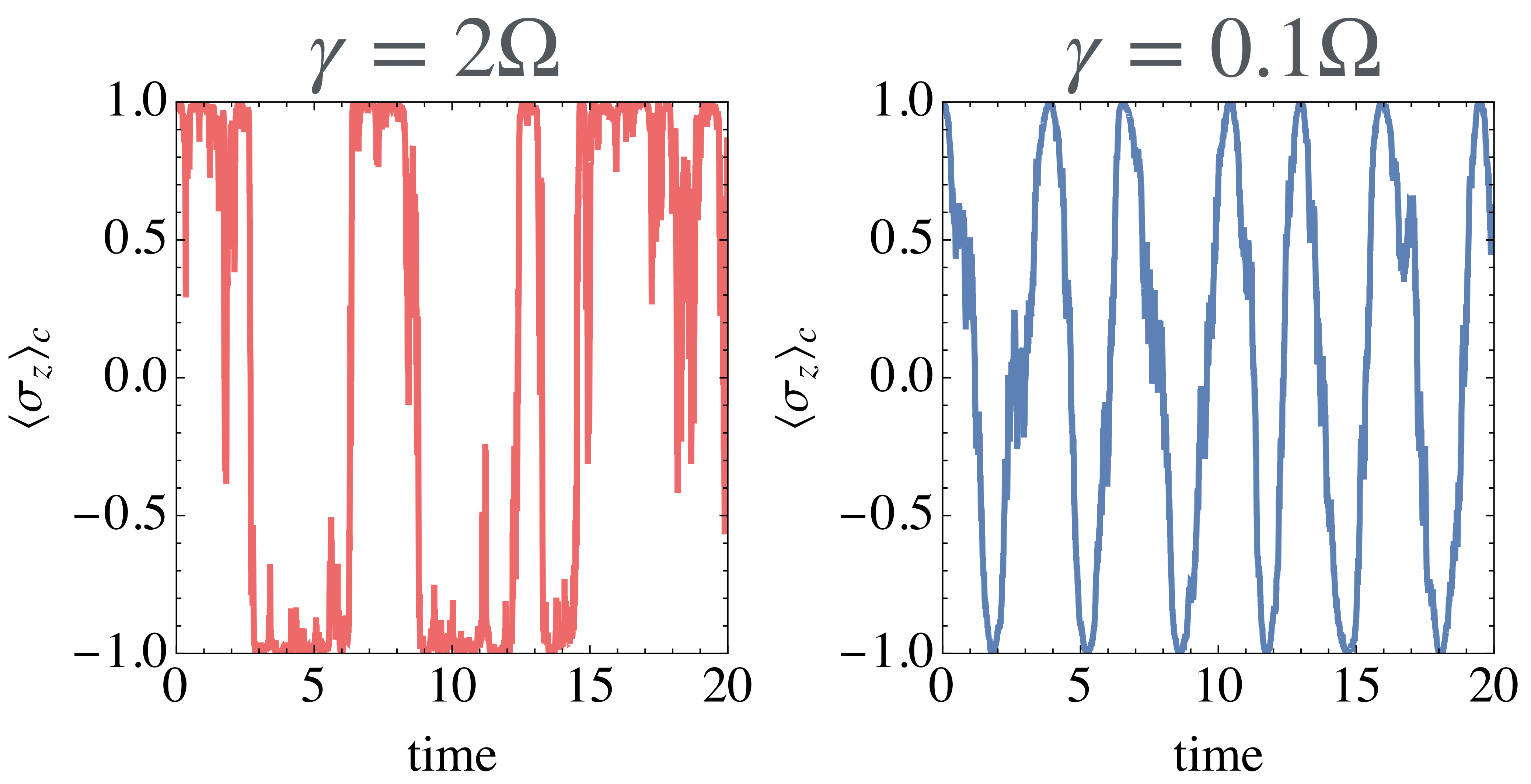
Fink *et. al.*, "**Signatures of a dissipative phase transition in photon correlation measurements**"
Nature Physics **14** 365-369 (2018)

Quantum jumps observed indirectly through continuous measurements of the system



Hofmann, *et. al.*
"**Measuring the Degeneracy of Discrete Energy Levels Using a GaAs / AlGaAs Quantum Dot**,"
Phys Rev. Lett **117**, 206803 (2016)

Driven qubit



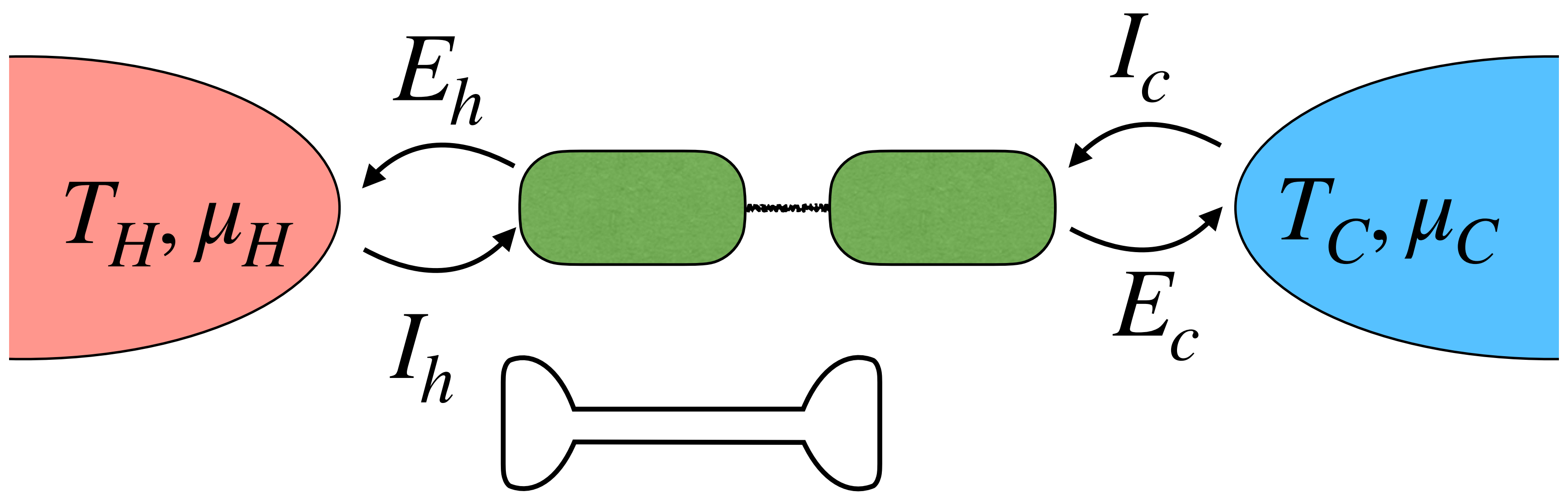
$$\frac{d\rho}{dt} = -i[\Omega\sigma_x, \rho] + \gamma D[\sigma_z]\rho$$

Double quantum dot - 3-level system

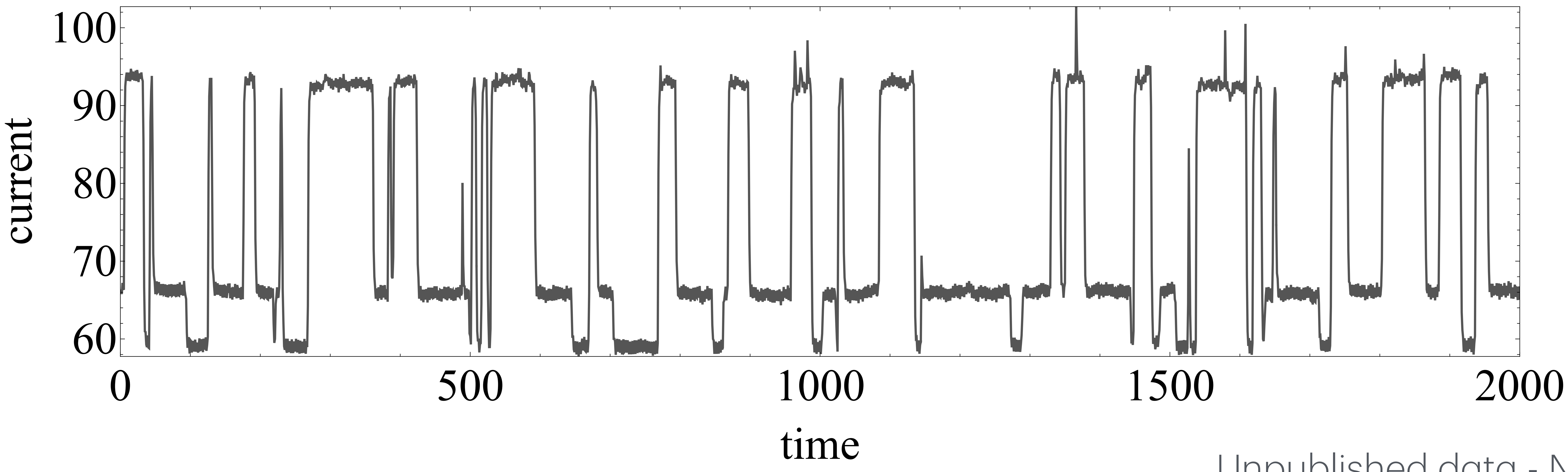
- Two dots + Coulomb blockade
  $\rightarrow$ 3 levels only: $|0\rangle, |L\rangle, |R\rangle$

- One-to-one mapping between system transition and jump channel

  - e.g. $|0\rangle \xrightarrow{I_H} |L\rangle$ or $|R\rangle \xrightarrow{E_C} |0\rangle$, etc.



QPC asymmetrically placed



Unpublished data - Natalia Ares' group

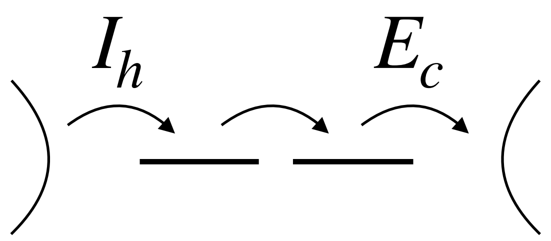
Stochastic operation of thermal machines

Patrick Potts

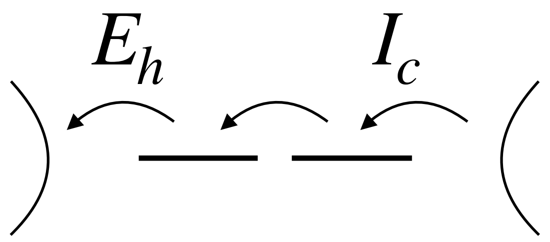
Abhaya Hegde

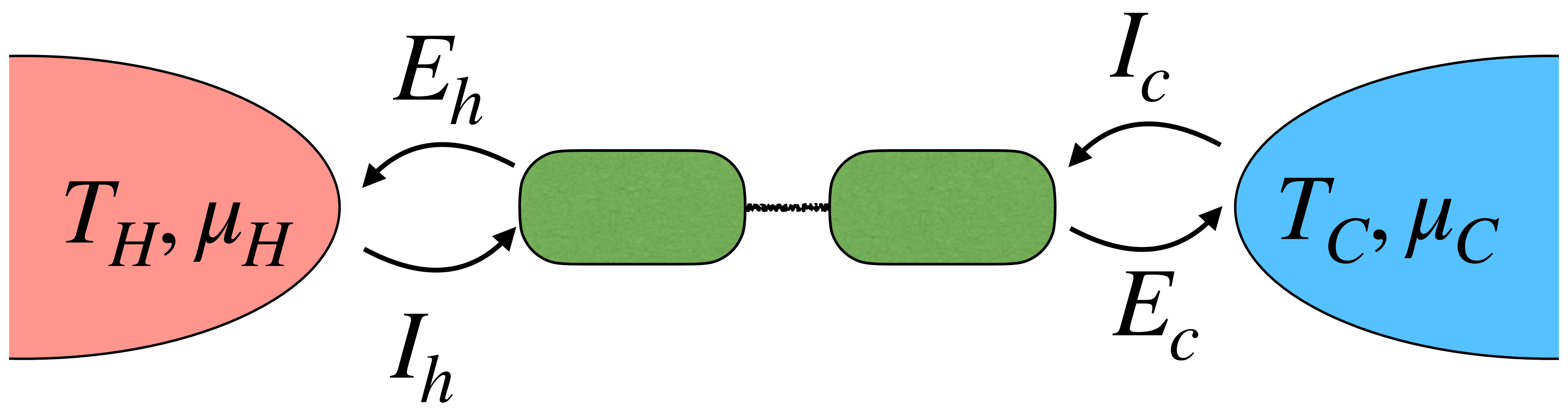
Abhaya S. Hegde, Patrick P. Potts, GTL, "**Time-resolved Stochastic Dynamics of Quantum Thermal Machines**," arXiv:2408.00694

- Double quantum dot
  - Engine process: uses thermal gradient to extract chemical work .

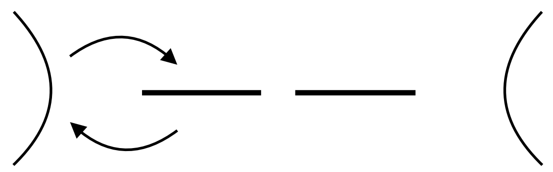


  - Refrigerator process: uses chemical work to make heat flow from cold to hot.

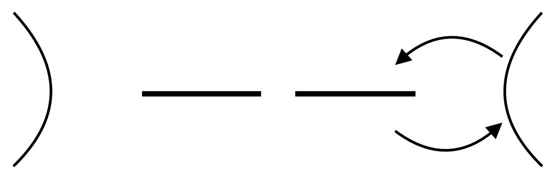




- There can also be “idle cycles” (bounces)
  - “Hot bounce”



  - “Cold bounce”



Can we identify individual cycles solely from a bitstring?

$I_h E_c I_c I_h E_h E_c I_h I_c E_h I_c$

Impossible in general, if excitations are indistinguishable

$$I_c I_h E_h E_c = \begin{cases} I_c I_h E_h E_c \\ I_c I_h E_h E_c \end{cases}$$

Manzano, Gonzalo, and Roberta Zambrini “**Quantum Thermodynamics under Continuous Monitoring: A General Framework**,” AVS Quantum Science 4 (2): 025302 (2022).

Single excitation assumption

$$\frac{d\rho}{dt} = \underbrace{-\,i[H,\rho]}_{\text{Unitary work}} + \underbrace{\sum_n D[K_n]\rho}_{\text{Work reservoirs}} + \sum_{\alpha\in\{h,c\}}\sum_j \underbrace{\gamma^-_{\alpha j} D[L_{\alpha j}]\rho}_{\text{Extraction to bath } \alpha} + \underbrace{\gamma^+_{\alpha j} D[L^\dagger_{\alpha j}]\rho}_{\text{Injection from bath } \alpha}$$

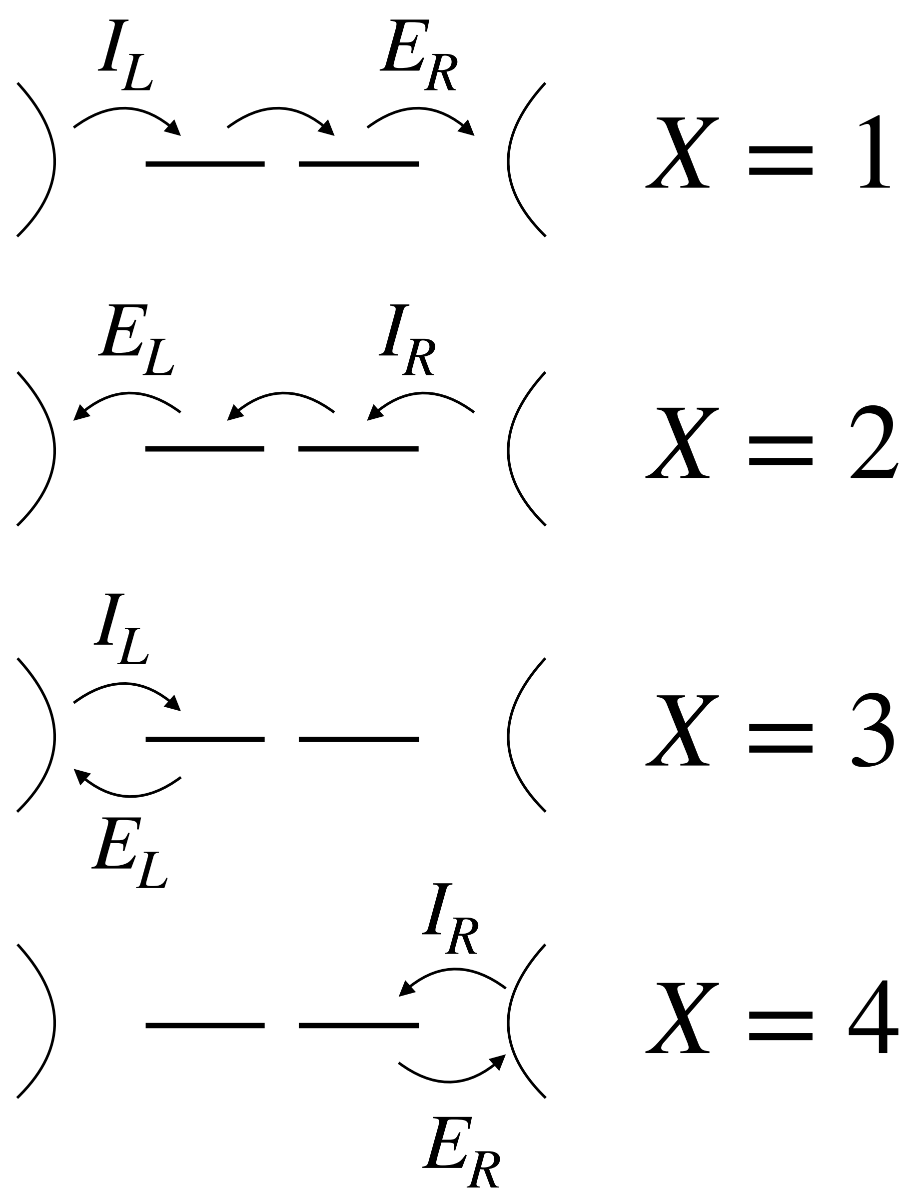
- Result: for cycles to be identifiable the string must always have injections followed by extractions.

$$\ldots I.E.I.E.I.E.I.E.I.E.\ldots$$

- Condition: Hilbert space must be split in 2.
  - $L^\dagger_{\alpha j}$ injects → post-injection subspace.
  - $L_{\alpha j}$ extracts → post-extraction subspace.

$$\text{Hilbert space} = \left(\begin{array}{c:c} \text{Post injection} & \\ \hdashline & \text{Post extraction} \end{array}\right)$$

Bitstrings of jumps → bitstrings of cycles



$$\ldots I_{\bullet}E_{\bullet}I_{\bullet}E_{\bullet}I_{\bullet}E_{\bullet}I_{\bullet}E_{\bullet}\ldots = \ldots X_{\bullet}X_{\bullet}X_{\bullet}X_{\bullet}\ldots$$

- We can use this to answer the following questions:
  - What is the probability that the next cycle is of type X and takes a time $\boldsymbol{\tau}$?
  - How are cycles correlated with each other?
  - What is the average time required to complete each cycle?
  - How many idle cycles happen between two useful cycles?
- Define instruments

$$M_{X\tau} = \int_0^\tau dt \; \mathcal{J}_{E_X} e^{\mathcal{L}_0(\tau - t)} \mathcal{J}_{I_X} e^{\mathcal{L}_0 t}$$

with 2 emitted symbols: $X = 1,2,3,4$ and cycle duration τ

Cycle probabilities

π_E = Jump Steady-State

Correct state to get long-time statistics

- Then prob. a cycle is of type X and takes a time τ: $p_{X,\tau} = \mathrm{tr}\{M_{X\tau}\pi_E\}$.

- If we don't care about how long a cycle takes, we just need to marginalize the instrument:

$$M_X = \int_0^\infty d\tau\ M_{X\tau}$$

- Prob. of obtaining each cycle type

$$p_X = \mathrm{tr}\{M_X \pi_E\}$$

- Conditional cycle times: if cycle is of type X, how long it takes?

$$E(\tau|X) = \int_0^\infty d\tau\ \tau \frac{p_{X,\tau}}{p_X}$$

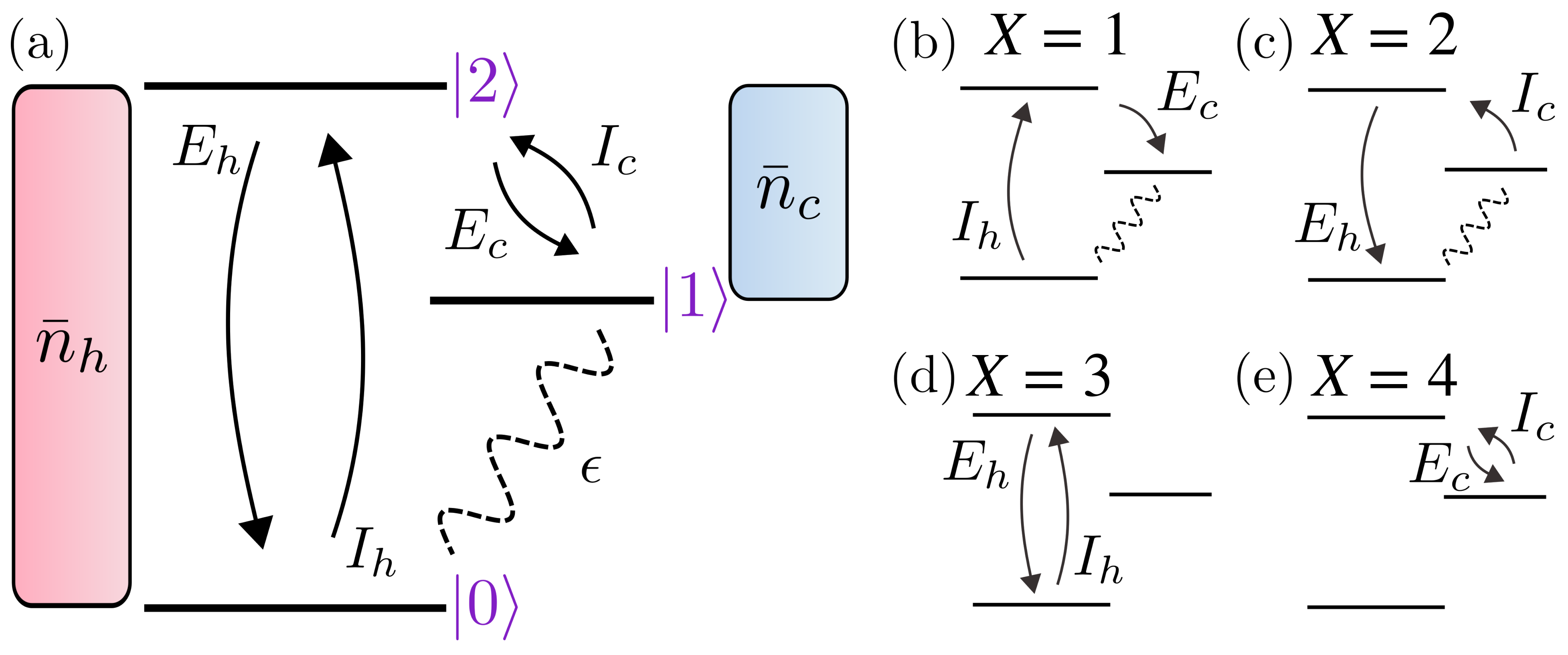
Relation to steady-state currents:

$$I = \frac{p_1 - p_2}{E(\tau)}$$

Correlations between cycles:

$$P(X_1, \tau_1, \ldots, X_n, \tau_n) = \mathrm{tr}\{M_{X_n\tau_n} \ldots M_{X_1\tau_1}\pi_E\}$$

Double quantum dot or 3-level system



$$\langle n \rangle = \frac{p_{\mathrm{id}}}{p_u} = \frac{p_3 + p_4}{p_1 + p_2}, \qquad T = \frac{p_3 E(\tau\,|\,3) + p_4 E(\tau\,|\,4)}{p_1 E(\tau\,|\,1) + p_2 E(\tau\,|\,2)},$$

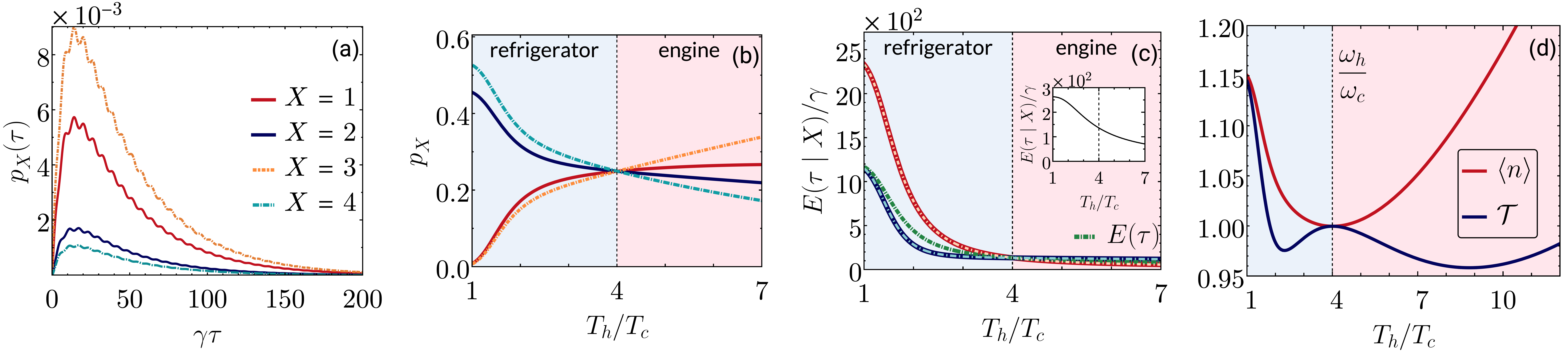


FIG. 3. **(a-d)** Statistics of cycles in three-level maser from Fig. 2. **(a)** Probability of observing a cycle X within a duration τ [Eq. (9)] at resonance $\omega_d = \omega_h - \omega_c$ and $T_h/T_c = 10$. **(b)** Total probability of observing a cycle X [Eq. (10)] and **(c)** expectation values for cycle duration [Eqs. (11), (12)] as a function of the ratio of bath temperatures. A vertical line at $T_h/T_c = \omega_h/\omega_c$ separates the refrigerator and engine regimes. The inset shows all expectation values nearly converge at resonance. **(d)** Mean of intervening idle cycles between useful cycles and ratios of fraction of idle-to-useful times against bath gradient. The parameters are fixed (in units of $T_c = 1$) at $\gamma_h = \gamma_c \equiv \gamma = 0.05$, $\omega_h = 8$, $\omega_c = 2$, $\omega_d = 4$, $\epsilon = 0.5$ unless mentioned otherwise.

Stochastic excursions


Guilherme Fiusa


Abhaya Hegde


Pedro Harunari

See also poster by Guilherme Fiusa this afternoon!

From quantum to classical master equation

- Any quantum master equation

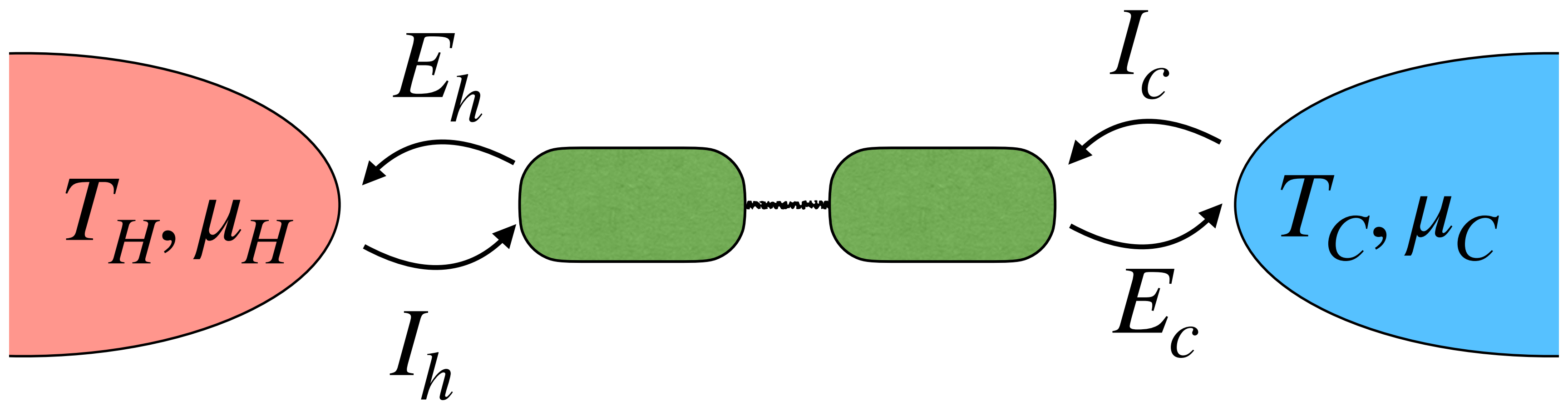
$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_k D[L_k]\rho$$

- Can be converted to a classical rate equation. Define $\rho_t = \sum_x p_x(t)\,|x_t\rangle\langle x_t|$. Then

$$\frac{dp_x}{dt} = \sum_{y\neq x} \left\{ W_{xy}(t)p_y - W_{yx}(t)p_x \right\}, \qquad W_{xy}(t) = \sum_k |\langle x_t|L_k|y_t\rangle|^2$$

- If eigenbasis of $\rho(t)$ does not change in time, the rate equation *fully* specifies the dynamics.

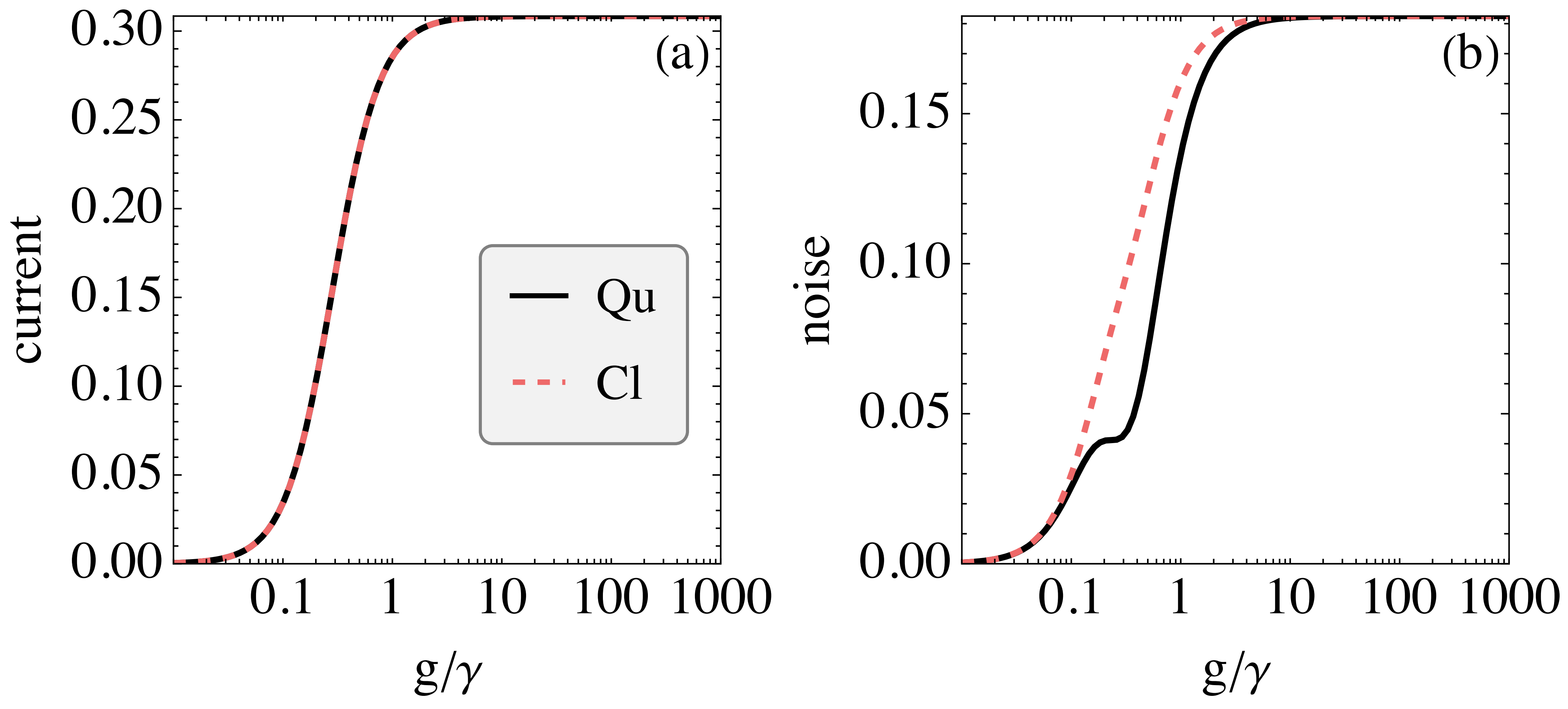
- Also useful as an approximation technique. Ex:



$$\frac{d\rho}{dt} = -i[g(c_1^\dagger c_2 + c_2^\dagger c_1), \rho] + \gamma_h(1-f_h)D[c_1] + \gamma_h f_h D[c_1^\dagger] + \gamma_c(1-f_c)D[c_2] + \gamma_c f_c D[c_2^\dagger]$$

- In the basis $|0\rangle, |L\rangle, |R\rangle$

$$W = \begin{pmatrix} 0 & \gamma_h(1-f_h) & \gamma_c(1-f_c) \\ \gamma_h f_h & 0 & \frac{4g^2}{\gamma_h+\gamma_c} \\ \gamma_c f_c & \frac{4g^2}{\gamma_h+\gamma_c} & 0 \end{pmatrix}$$



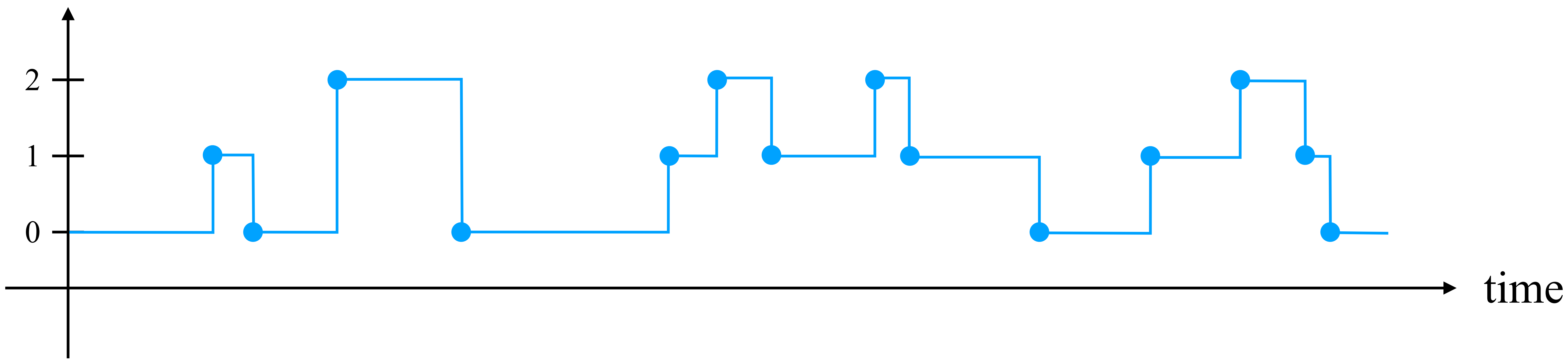
- Derived using perturbation theory

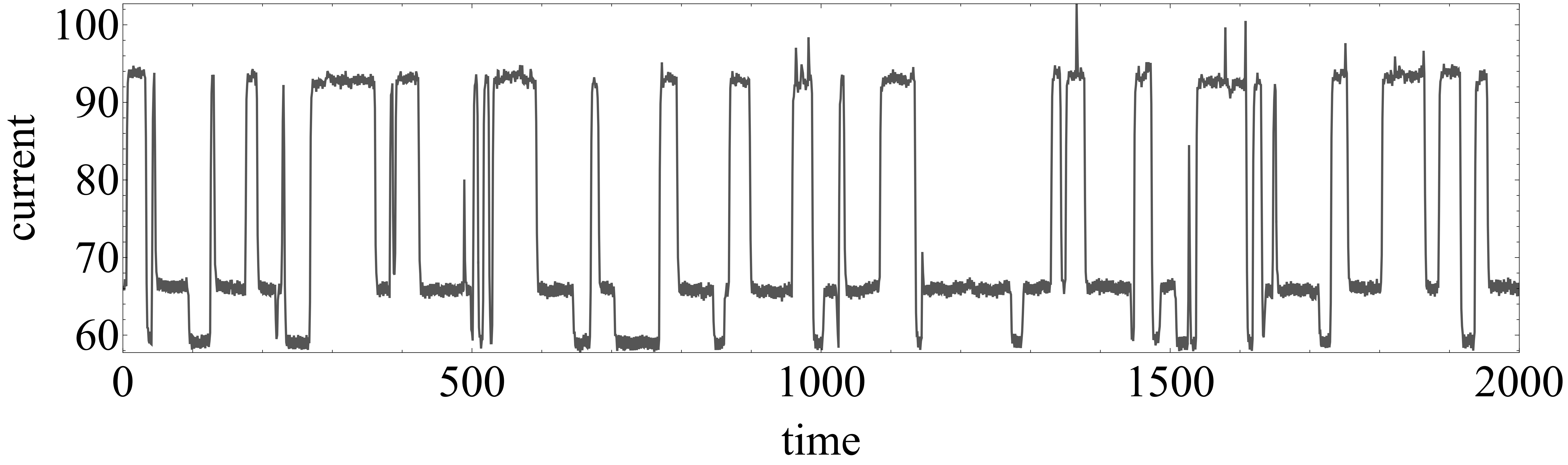
Exact for the average current.
Pretty good for the fluctuations.

K. Prech, P. Johansson, E. Nyholm ,GTL, C. Verdozzi , P. Samuelsson , P. P. Potts
"**Entanglement and thermokinetic uncertainty relations in coherent mesoscopic transport**". Phys. Rev. Res. 5, 023155 (2023).

Counting observables

- Steady-state = ensemble thing.
- At the stochastic level, system is always jumping up and down.





Counting variables $\hat{N}_{xy}(t)$

Build physical currents through counting observables

$$\hat{Q}(t) = \sum_{x,y} \nu_{x,y} \hat{N}_{xy}(t)$$

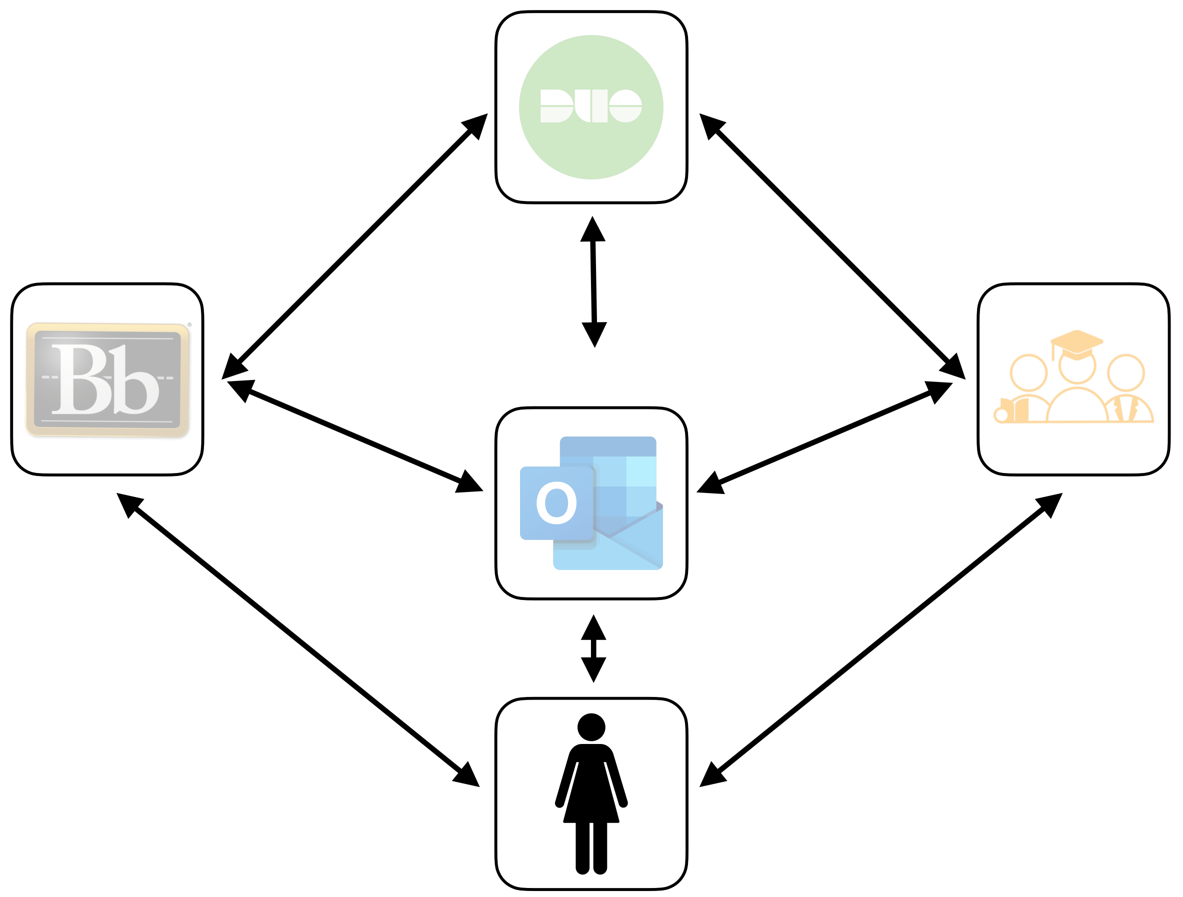
Weights ν_{xy} determine the physics.

Example: current to the left bath

$$\nu_{0L} = -\nu_{L0} = 1$$

Beyond physics:

ν_{xy} appends contextual meaning



Full Counting Statistics

- FCS deals with the long-time statistics of counting observables.

- Define the tilted matrix (ξ = counting field)

$$\mathbb{W}^{\xi}_{xy} = \begin{cases} W_{xy} e^{i\xi\nu_{xy}} & x \neq y \\ -\sum_z W_{zx} & x = y \end{cases}$$

- And define the generalized master equation

$$\frac{dp^{\xi}_x}{dt} = \sum_y W^{\xi}_{xy} p^{\xi}_y$$

Then

$$P_t(\mathcal{Q}) = \int_{-\infty}^{\infty} \frac{d\xi}{2\pi} e^{-i\xi\mathcal{Q}} \Big(\sum_x p^{\xi}_x \Big)$$

All cumulants are extensive:

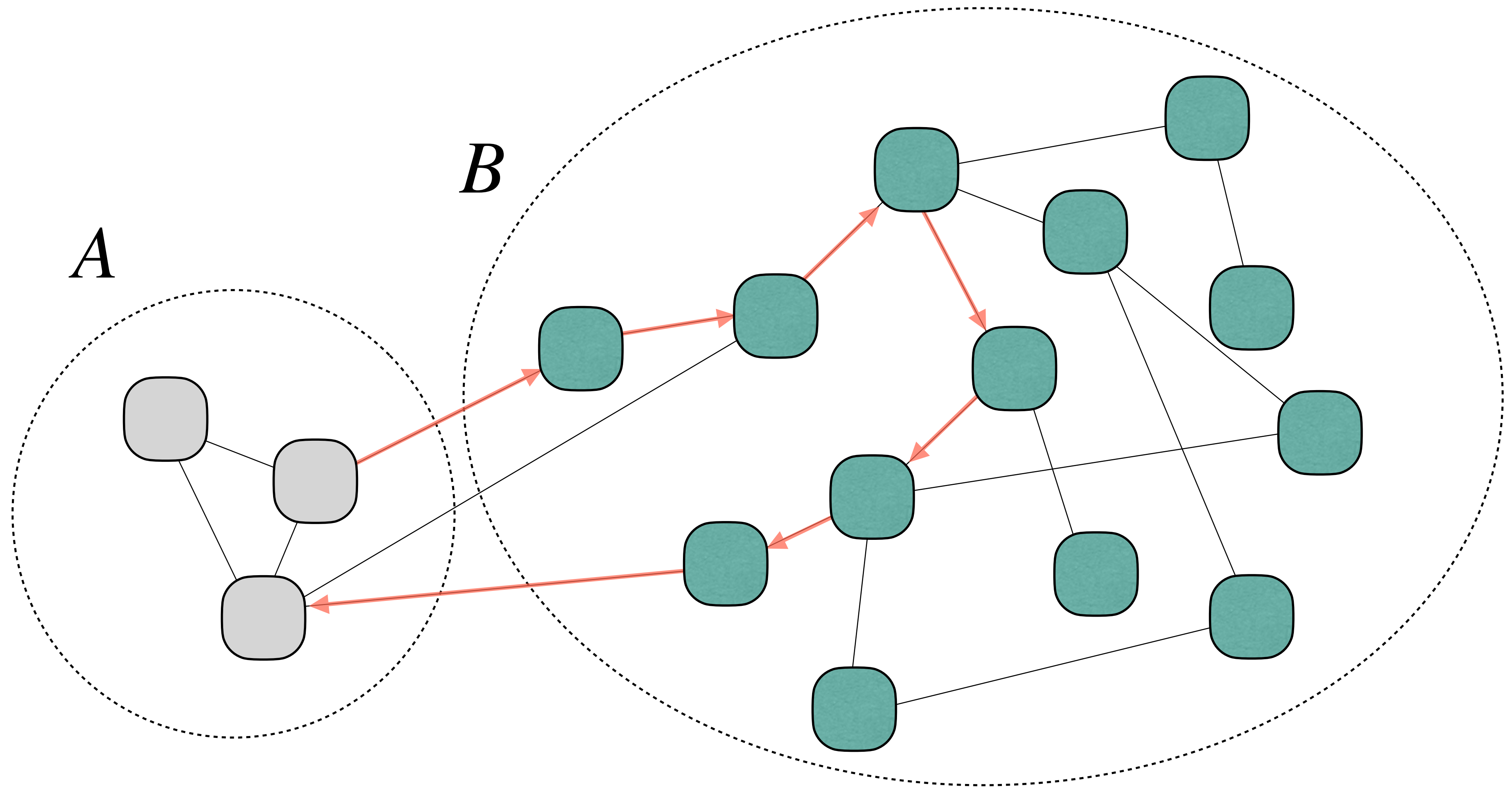
$E(\mathcal{Q}) = Jt \quad (J = \text{current})$

$\mathrm{var}(\mathcal{Q}) = Dt$

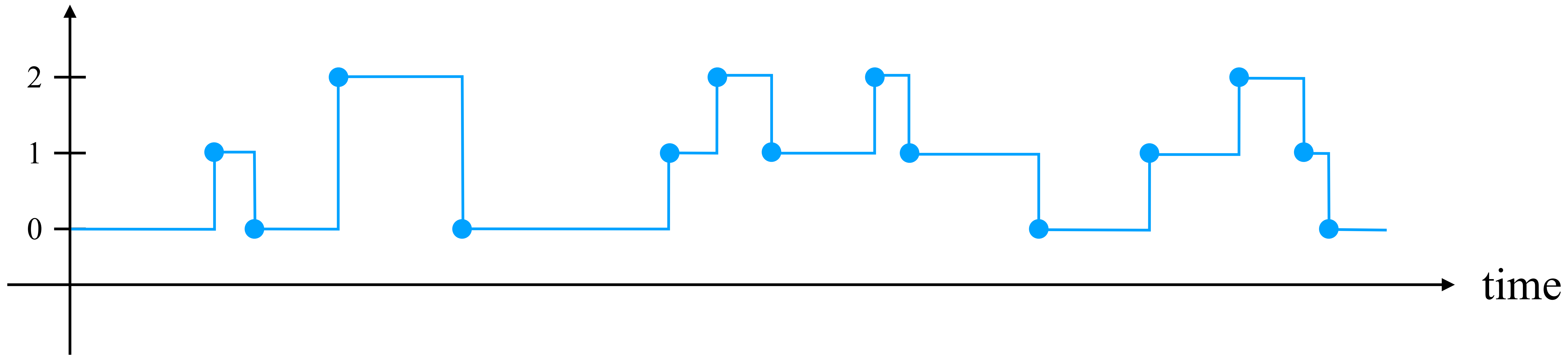
$D =$ noise/diffusion coefficient/scaled variance.
(not an actual variance)

D is the thing in a TUR.

Stochastic excursions



- Starts when system leave A.
- Ends when system first comes back to A.
- Generalizes the notion of cycles.
- Excursion time $\hat{T}$ is random: **first passage time**. Well known and extensively studied.
- Our question: **statistics of counting observables within a single excursion $\hat{Q}(\hat{T})$.**

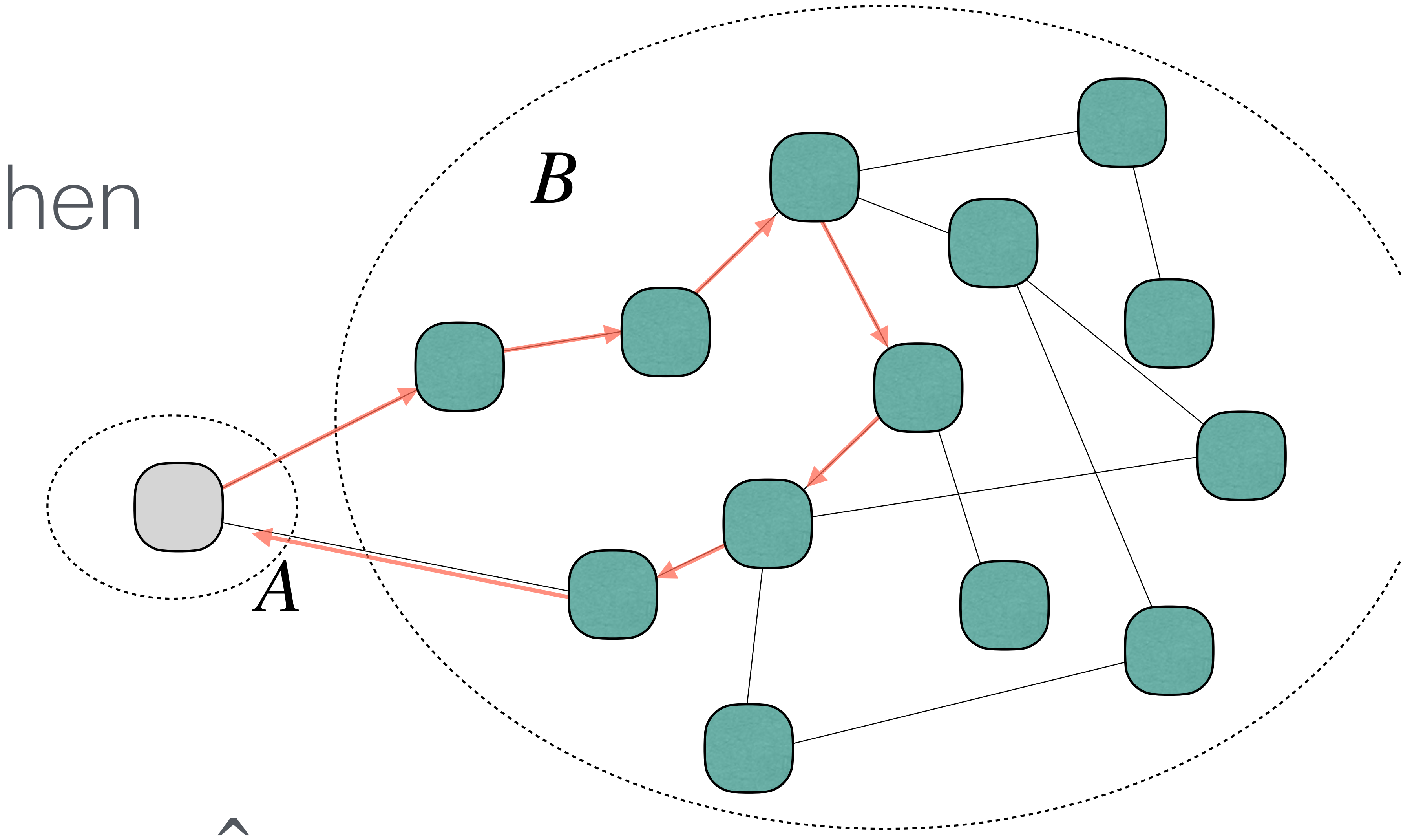


Ongoing work

- We have found a way to compute $P(Q, T)$: joint prob. that excursion takes a given time and counting observable has a given value. Can also compute $P(Q_1, Q_2, \ldots, T)$.

- **Exchange FT:** if $\hat{Q} = \hat{\Sigma}$ = entropy production then $P(\Sigma) = e^{-\Sigma} P(-\Sigma)$.
    - Valid at the level of a single excursion.

- Connection with steady-state quantities: let $\hat{T}_{\text{tot}} = \hat{T} + \hat{T}_{\text{res}}$. Then

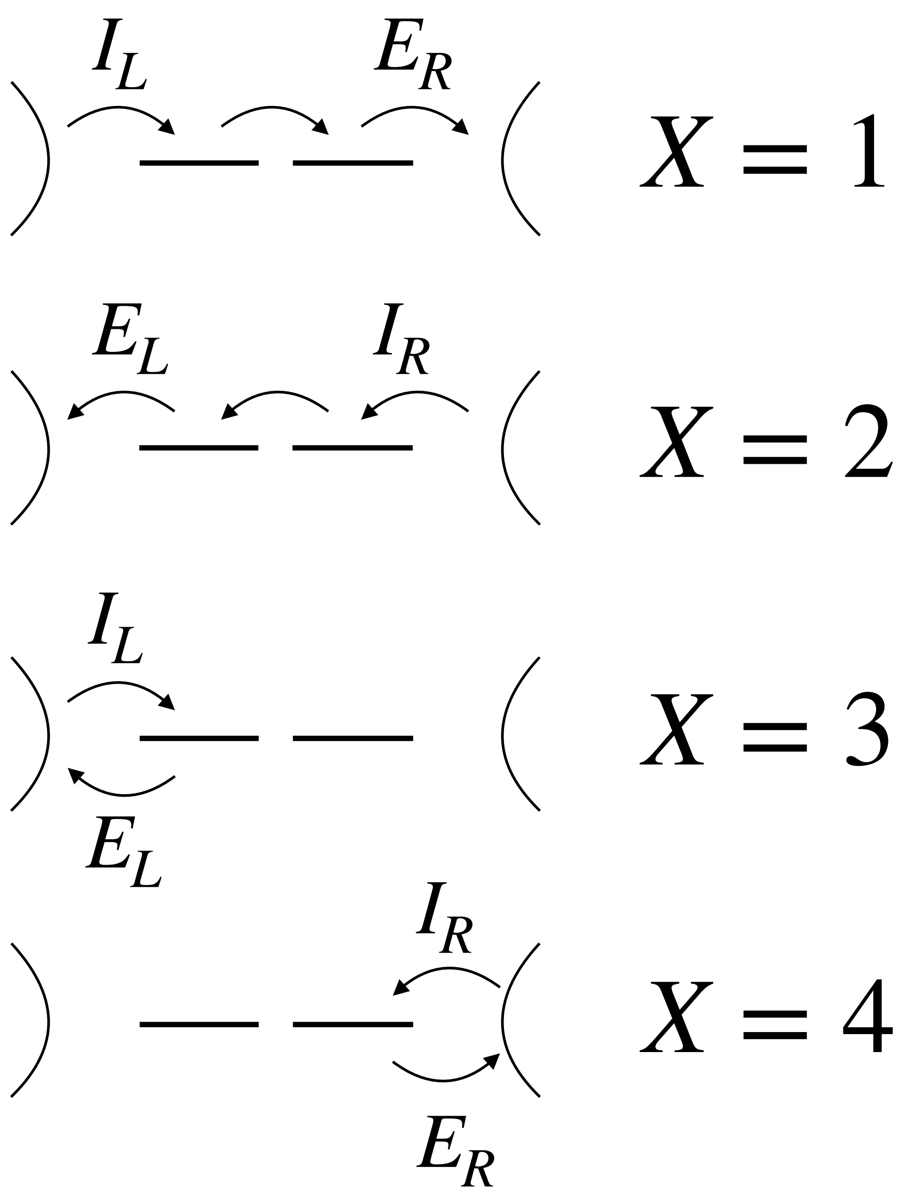


$$J = \frac{E(\hat{Q})}{\mu} \quad \text{where} \quad \mu = E(\hat{T}_{\text{tot}})$$

$$D = \frac{\text{var}(Q)}{\mu} + \frac{E(\hat{Q})\Delta^2}{\mu^3} - \frac{2E(\hat{Q}}{\mu}\text{cov}(\hat{Q}, \hat{T}) \quad \text{where} \quad \Delta^2 = \text{var}(\hat{T}_{\text{tot}}).$$

Conclusions

- Sequential quantum measurements = **time-series** of correlated stochastic outcomes.
  - Bayesian inference of the quantum state, given outcomes.
  - Unveiling the thermodynamics from measurement data.
  - Stochastic operation of a thermal machine.
    - Open question: machine intermittency vs. current fluctuations?
  - Stochastic excursions: so far classical, but very exciting.



GTL, Michael J. Kewming, Mark T. Mitchison, Patrick P. Potts "**Current fluctuations in open quantum systems: Bridging the gap between quantum continuous measurements and full counting statistics**," PRX Quantum 5, 020201 (2024)

GTL "**Patterns in the jump-channel statistics of open quantum systems**," arXiv 2305.07957

Abhaya S. Hegde, Patrick P. Potts, GTL, "**Time-resolved Stochastic Dynamics of Quantum Thermal Machines**," arXiv:2408.00694

Conclusions

Thank you!

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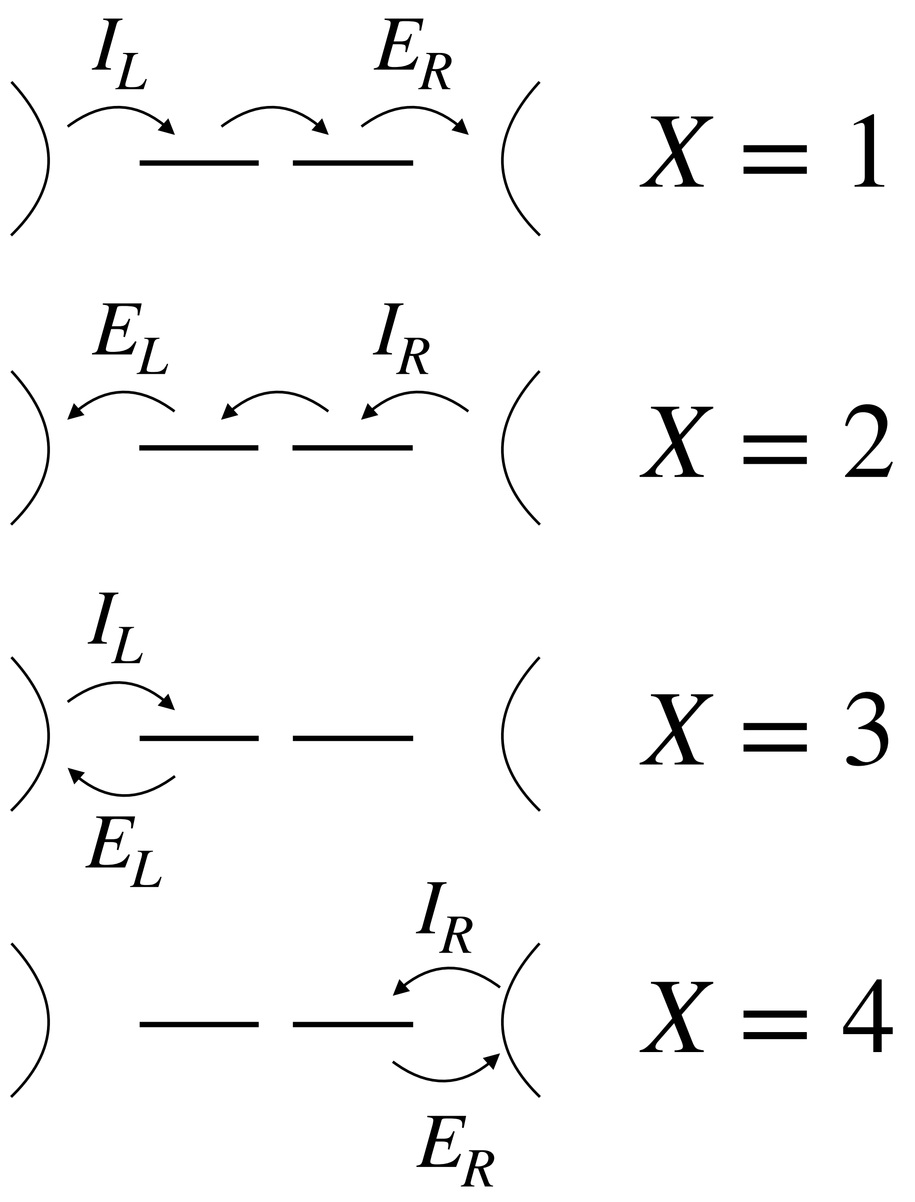

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