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Parameter estimation in the presence of temporal correlations

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Quantum Trajectories, ICTS
27 Jan 2025

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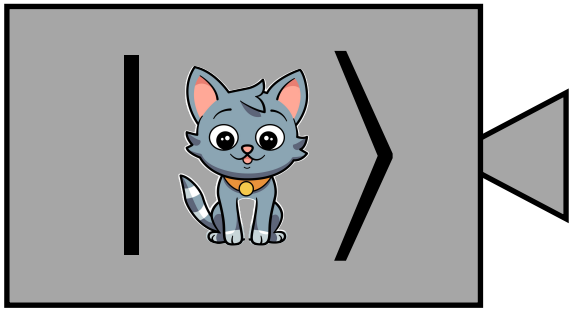
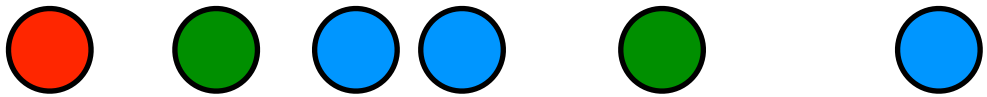


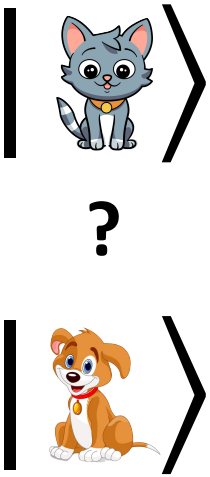
Open quantum system



Emissions

$$\omega_N = (x_1, x_2, \ldots, x_N)$$

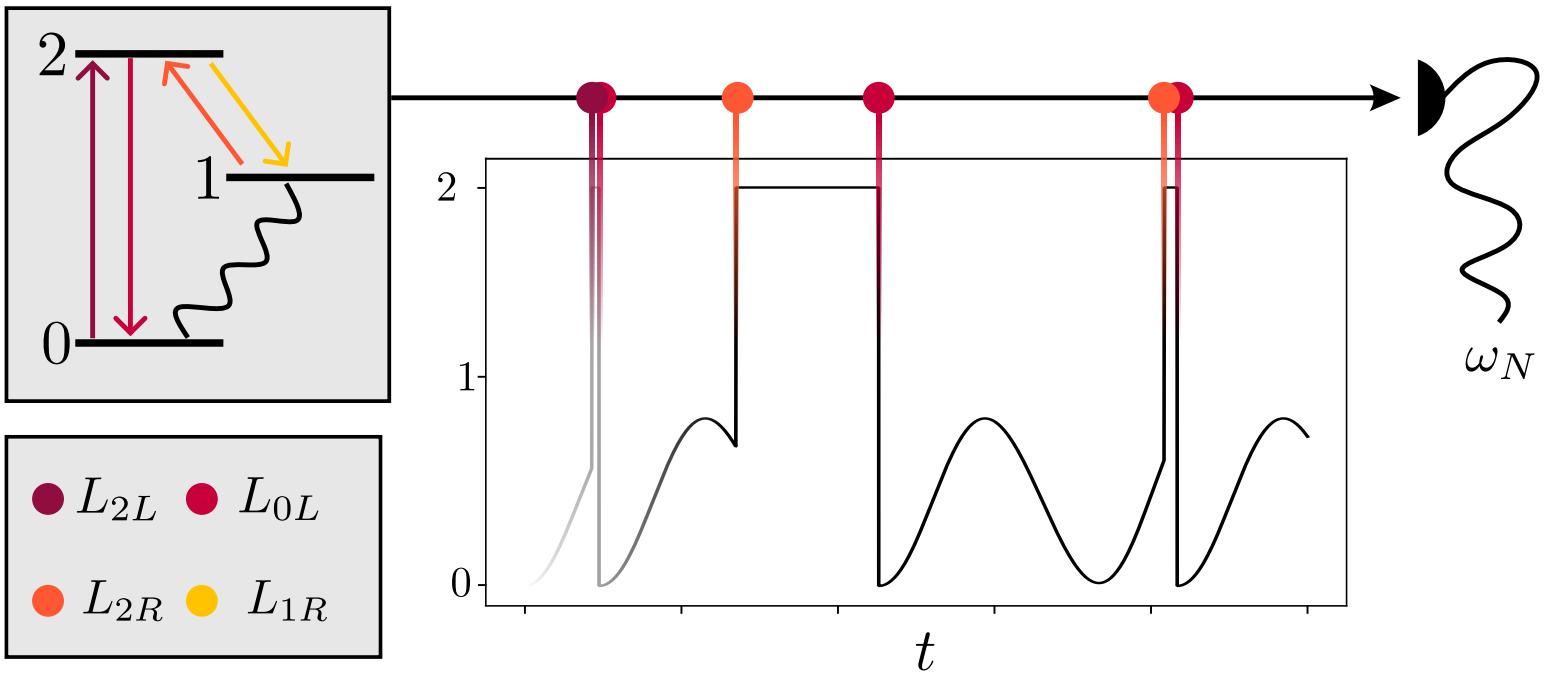
Measurement record



What can we learn about a quantum system by looking at the **measurement record**?

And, how to understand and exploit the power of **temporal correlations** in the measurement record?

Learning from emissions in time

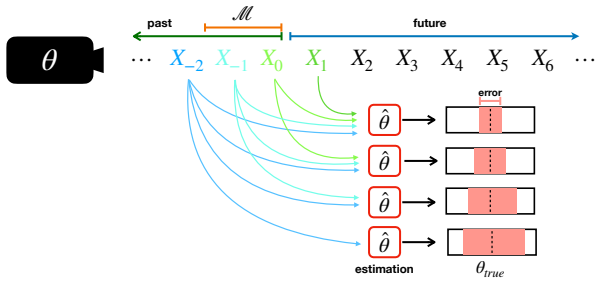


Measurement record $\omega_N = \{(k_1, \tau_1), (k_2, \tau_2), \ldots, (k_N, \tau_N)\}$

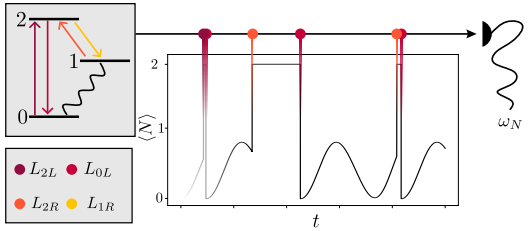
How precisely can we **estimate** a **parameter** encoded in the **dynamics** by starting from the measurement record?

Contents

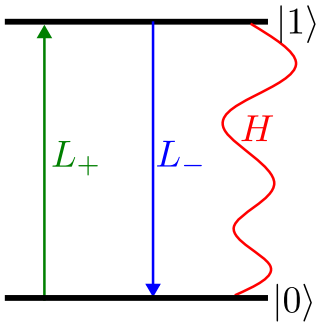
(Correlated) estimation theory



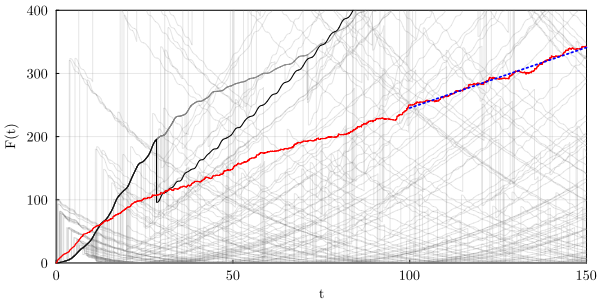
Quantum Jump Unraveling



Renewal processes

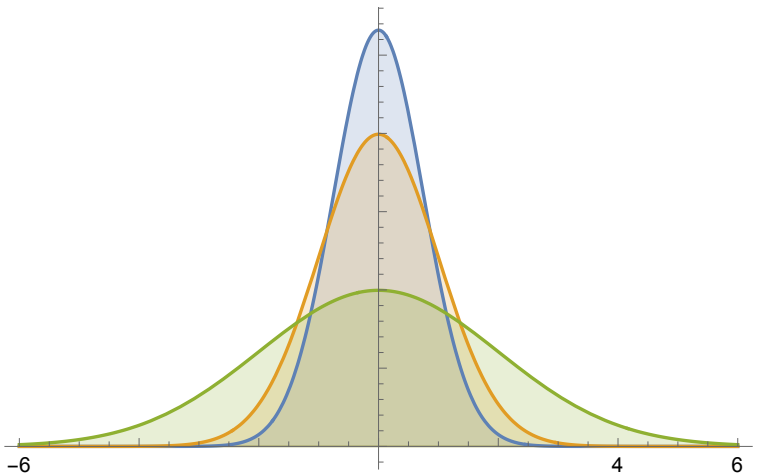


Non-renewal processes



Classical estimation theory

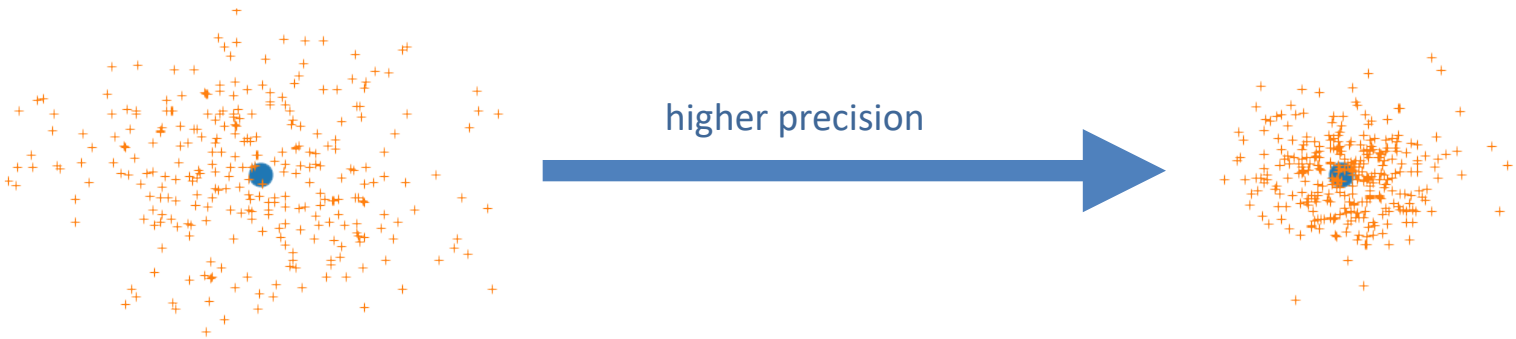
P_θ —sampling→ $X_1, X_2, X_3, \ldots$



Parameter-dependent probability distribution

$X_1, X_2, X_3, \ldots$ → Estimator $T(\vec{X})$ → $\hat{\theta}$

Classical estimation theory



Cramér-Rao bound

$$\mathbb{E}_{X_{1:N}}\left[\left(\hat{\theta}-\theta\right)^2\right] \geq \frac{1}{F_{1:N}(\theta)}$$

Fisher information for the set of random variables $X_1, \ldots, X_N$

Classical estimation theory

The Fisher information is defined as:

$$F_{1:N}(\theta) = \sum_{x_1 \ldots x_N} p_\theta(x_1 \ldots x_N) \left(\frac{\partial}{\partial \theta} \log p_\theta(x_1 \ldots x_N) \right)^2$$

$$= - \underbrace{\sum_{x_1 \ldots x_N}}_{\mathbb{E}_{X_{1:N}}} p_\theta(x_1 \ldots x_N) \underbrace{\frac{\partial^2}{\partial \theta^2} \log p_\theta(x_1 \ldots x_N)}_{\text{How strongly does } p \text{ depend on } \theta?}$$

Classical estimation theory

I.i.d. random variables

$$p(X_1 \ldots X_N) = p(X_1) \cdot \ldots \cdot p(X_N)$$

$$\Downarrow$$

$$F_{1:N}(\theta) = NF_1(\theta)$$

Cramér-Rao bound gives linear scaling of the precision

$$\mathbb{E}_{X_{1:N}}\left[\left(\hat{\theta} - \theta\right)^2\right] \geq \frac{1}{F_{1:N}(\theta)} = \frac{1}{NF_1(\theta)}$$

Extension to multiple parameters

Fisher information matrix

$$[F_{1:N}(\theta)]_{i,j} = \sum_w p_\theta(w)\left(\frac{\partial}{\partial\theta_i}\log p_\theta(w)\right)\left(\frac{\partial}{\partial\theta_j}\log p_\theta(w)\right)$$

Covariance matrix

$$[\sigma^2]_{i,j} = \sum_w p_\theta(w)\left(\hat{\theta}_i(w) - \theta_i\right)\left(\hat{\theta}_j(w) - \theta_j\right)$$

CR bound: $\sigma^2 \geq \dfrac{1}{F_{1:N}(\theta)}$ $\left(\sigma^2 - F_{1:N}^{-1}(\theta)\text{: positive semidefinite}\right)$

What about correlations?

Define conditional Fisher information

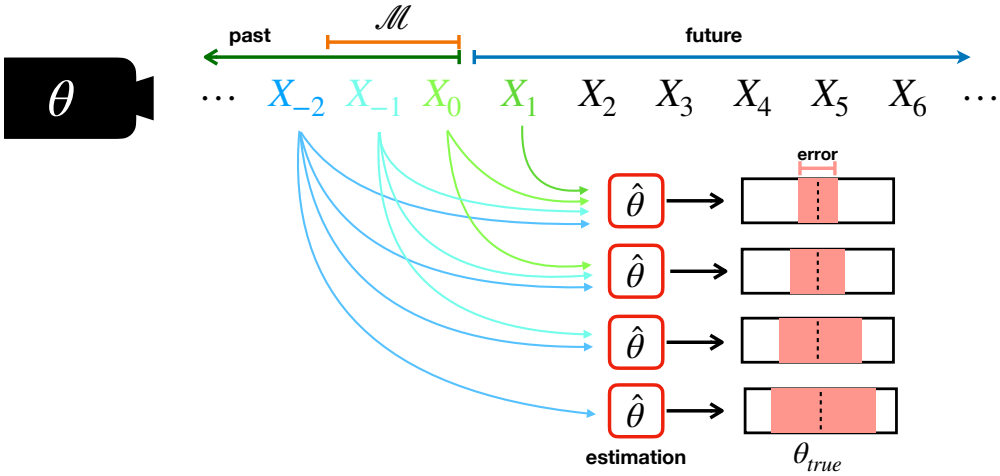
$$[F_{X_2|X_1}(\theta)]_{ij} = \sum_{x_1,x_2} p_\theta(x_1,x_2)\left(\frac{\partial}{\partial\theta_i}\log p_\theta(x_2\,|\,x_1)\right)\left(\frac{\partial}{\partial\theta_j}\log p_\theta(x_2\,|\,x_1)\right)$$

Chain rule:

$$F_{X_2|X_1}(\theta) = F_{X_1,X_2}(\theta) - F_{X_1}(\theta)$$

For 1:N:

$$F_{1:N}(\theta) = F_1(\theta) + \sum_{k=2}^{N} F_{k|1:k-1}(\theta)$$



Zegers, *Entropy* **17**, 4918 (2015)
Micadei et al., *New J. Phys.* **17,** 023057 (2015)
Radaelli, Landi, Modi, Binder, *New J. Phys.* **25** 053037 (2023)

Memory and Markov order

Stationary process

$$p\left(X_{0:L} = w\right) = p\left(X_{K:K+L} = w\right) \quad \forall K \in \mathbb{Z}, L \in \mathbb{N}, w \in \mathscr{A}^L$$ (No explicit time dependence)

Markov order

$$\mathscr{M} = \min\left\{R \text{ s.t. } p\left(X_0 | X_{-R:0}\right) = p\left(X_0 | X_{-\infty:0}\right)\right\},$$ (Truncate conditionals at -M)

E.g. Markov chain $\mathscr{M} = 1$, i.i.d. variables $\mathscr{M} = 0$.

Memory and the Markov order

Finite Markov order $\mathscr{M}$ + stationary process

$$\boxed{F_{1:N}(\theta) = F_{1:\mathscr{M}}(\theta) + (N - \mathscr{M})F_{\mathscr{M}+1|1:\mathscr{M}}(\theta)}$$

CR bound:

$$\mathbb{E}_{X_{1:N}}\left[\left(\hat{\theta} - \theta\right)^2\right] \geq \frac{1}{F_{1:N}(\theta)} = \frac{1}{F_{1:\mathscr{M}}(\theta) + (N - \mathscr{M})F_{\mathscr{M}+1|1:\mathscr{M}}(\theta)} \sim \frac{1}{NF_{\mathscr{M}+1|1:\mathscr{M}}(\theta)}$$

Still linear, but with a different slope.

Memory and the Markov order

CR bound:

$$\sigma^2 \geq \frac{1}{F_{1:N}(\theta)}$$

Finite Markov order $\mathscr{M}$:

$$\frac{1}{F_{1:N}(\theta)} = \frac{1}{F_{1:\mathscr{M}}(\theta) + (N - \mathscr{M})F_{\mathscr{M}+1|1:\mathscr{M}}(\theta)} \sim \frac{1}{NF_{\mathscr{M}+1|1:\mathscr{M}}(\theta)}$$

Cf. i.i.d. variables:

$$\frac{1}{F_{1:N}(\theta)} = \frac{1}{NF_1(\theta)}$$

=> Still linear, but with a different slope.

Thermometry on Ising spin chains

Consider a thermal state ($k_B = 1$):

$$p(X_1 \ldots X_N) = \frac{1}{Z} e^{-H(X_1 \ldots X_N)/T}$$

General connection between thermal state Fisher information for T and the heat capacity:

$$F(T) = \frac{C}{T^2} \qquad C = \frac{\partial \langle H \rangle}{\partial T} \qquad c = \frac{C(N)}{N}$$

$$\lim_{N \to \infty} \frac{c}{T^2} = f = F_{\mathscr{M}+1|1:\mathscr{M}}(T)$$

Thermometry on Ising spin chains

Ising Hamiltonian:

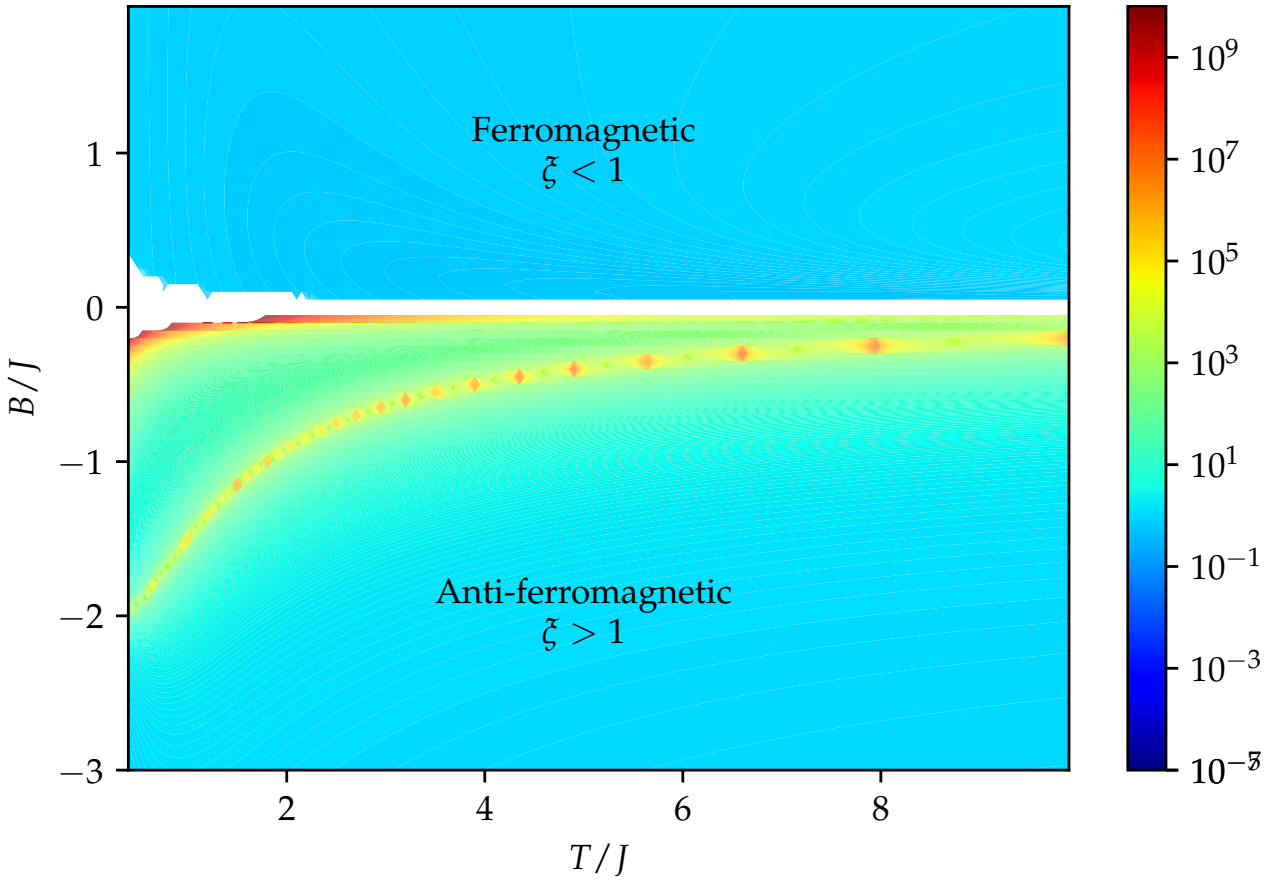
$$H = -B\sum_j \sigma_j^z - J\sum_j \sigma_j^z \sigma_{j+1}^z,$$

Thermal states of Ising chain Hamiltonian have **Markov order** $\mathscr{M} = 1$**.**

$$\xi = \frac{F_{1:2}(T)}{2F_1(T)}$$

=> $\xi > 1$: super-additive, $\xi < 1$: sub-additive.

Thermometry on Ising spin chains

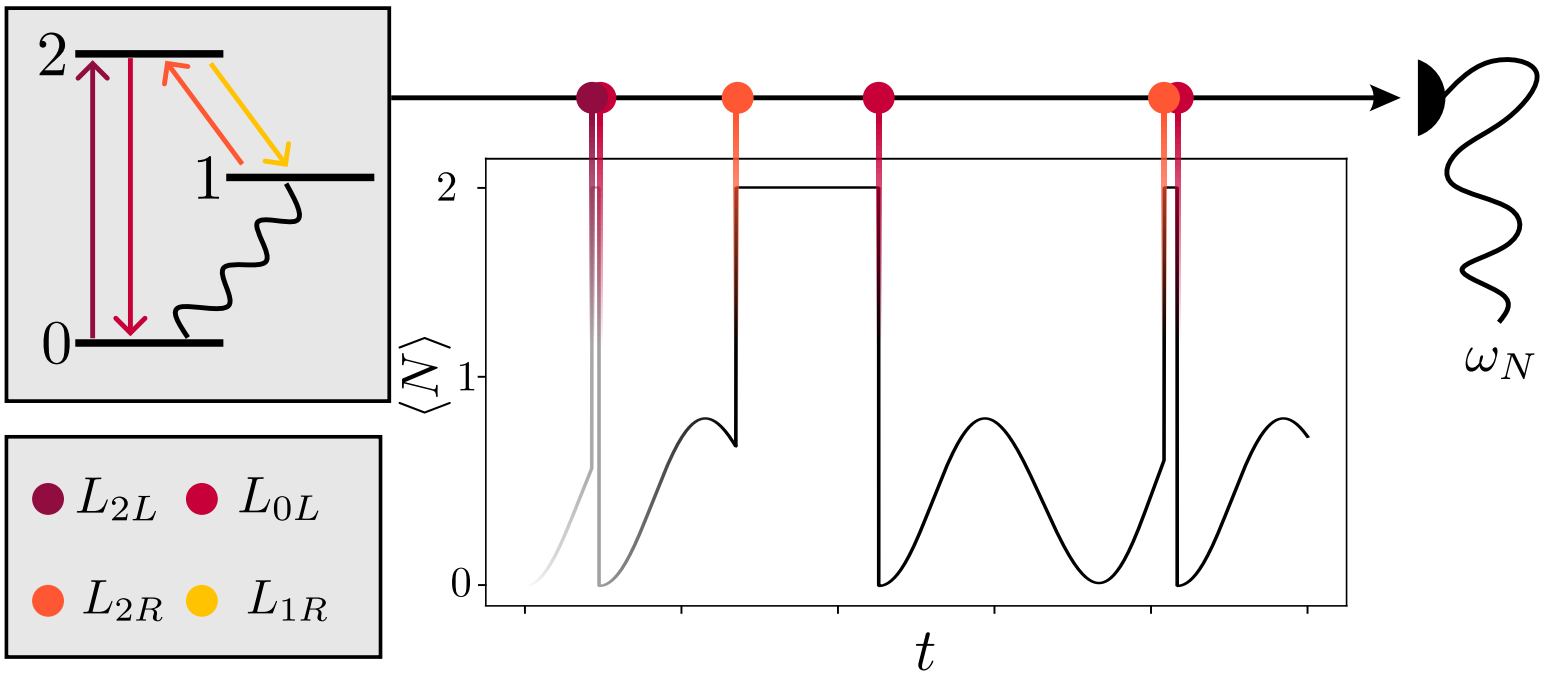


$$= \frac{F_{1:2}(T)}{2F_1(T)}$$

Take-home message #1

- I.i.d. hypothesis often does not hold.
- Finite Markov order $\mathscr{M}$ -> linear precision, different slope.
- Correlations can be helpful or detrimental for estimation.

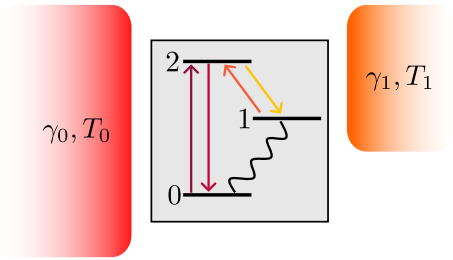
Learning from emissions in time



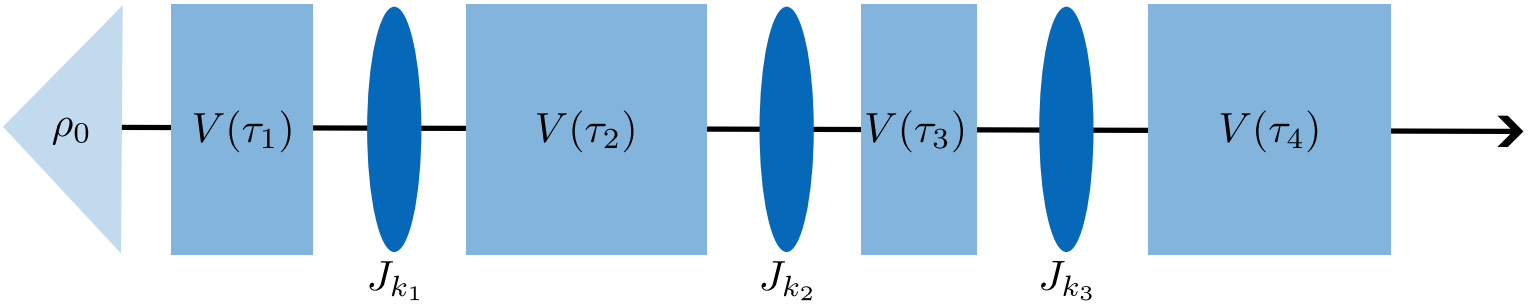
Measurement record $\omega_N = \{(k_1, \tau_1), (k_2, \tau_2), \ldots, (k_N, \tau_N)\}$

How precisely can we **estimate** a **parameter** encoded in the **dynamics** by starting from the measurement record?

Quantum Jump Unraveling (QJU)

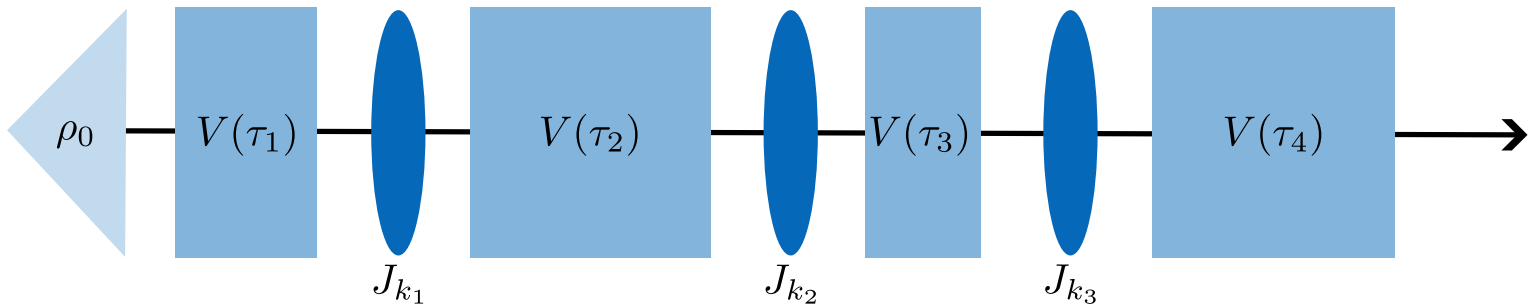


$$\frac{d\rho}{dt} = \mathscr{L}\rho = -i[H,\rho] + \sum_{k=1}^{r} \gamma_k \mathscr{D}\left[L_k\right]\rho$$



$$\mathscr{D}[L]\bullet = L\bullet L^{\dagger} - \frac{1}{2}\left\{L^{\dagger}L, \bullet\right\}$$

Quantum Jump Unraveling (QJU)



Jump super-operator

$$\mathscr{J}_k\rho = \gamma_k L_k \rho L_k^\dagger$$

No-jump super-operator

$$\mathscr{L}_0 = \mathscr{L} - \sum_{k\in\mathbb{M}} \mathscr{J}_k$$

No-jump evolution

$$V(\tau) = e^{\mathscr{L}_0\tau}$$

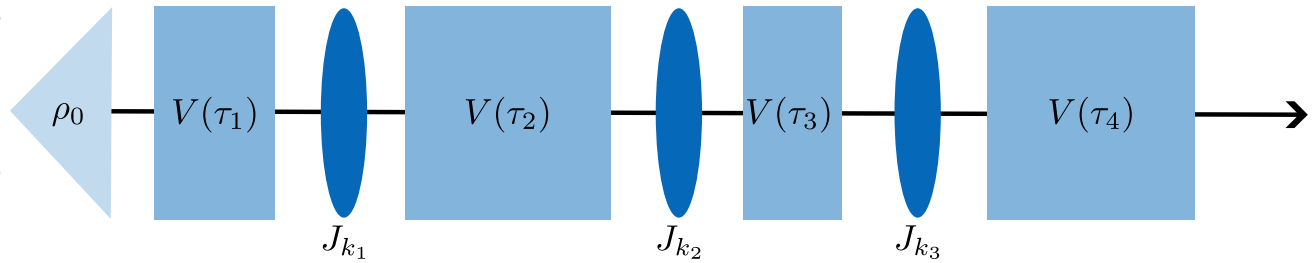
$$d\rho = dt\mathscr{L}\rho + \sum_k \left(dN_k(t) - dt\,\mathrm{Tr}[\mathscr{J}_k\rho]\right)\left(\frac{\mathscr{J}_k\rho}{\mathrm{Tr}[\mathscr{J}_k\rho]} - \rho\right)$$

Probability of a measurement sequence

Measurement record $\omega_{1:N} = \{(k_1, \tau_1), (k_2, \tau_2), \ldots, (k_N, \tau_N)\}$

$$Pr(\omega_{1:N}) = \text{Tr}\left[\mathcal{J}_{k_N} e^{\mathcal{L}_0 \tau_N} \ldots \mathcal{J}_{k_1} e^{\mathcal{L}_0 \tau_1} \rho_0\right]$$

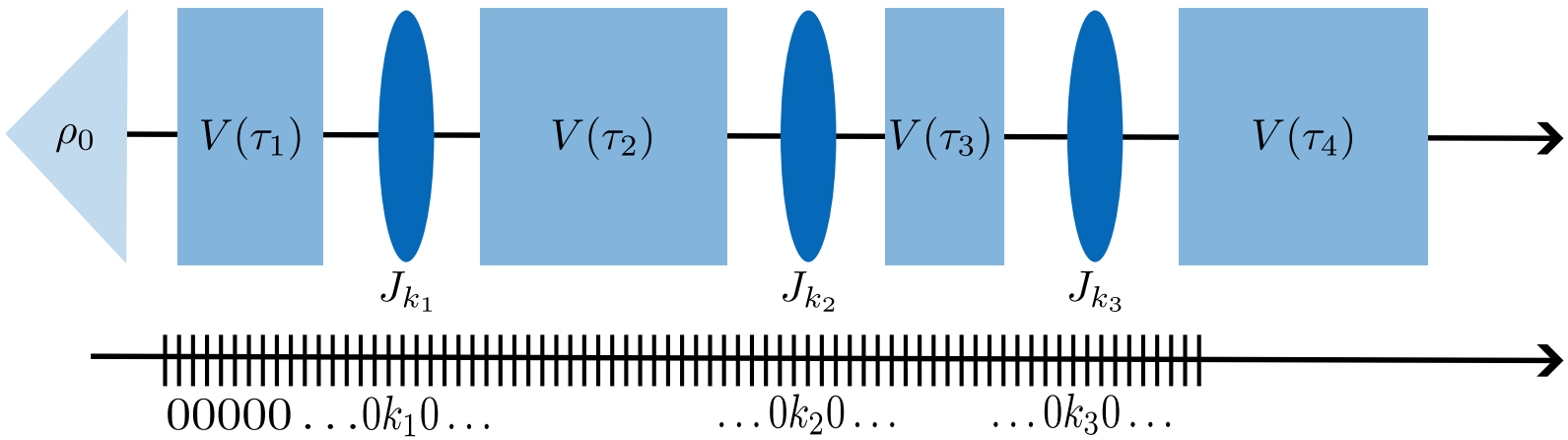
Tr



What is the **Fisher information** contained in the **measurement record**?

N and t_f ensembles

N-ensemble $\omega_{1:N} = \{(k_1, \tau_1), (k_2, \tau_2), \ldots, (k_N, \tau_N)\}$ $N \to \infty$



t_f-ensemble $\omega_t = \{x_0, x_1, \ldots, x_t\}$ $dt \to 0$

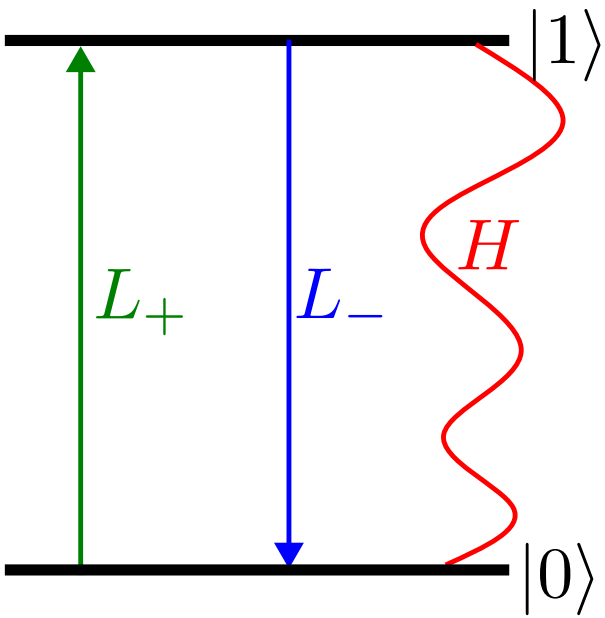
(Multi-channel) renewal processes

=> jump fully determines the next state

$$\mathcal{J}_k \rho = \mathrm{Tr}\left[\mathcal{J}_k \rho\right] \sigma_k$$

A simple example:

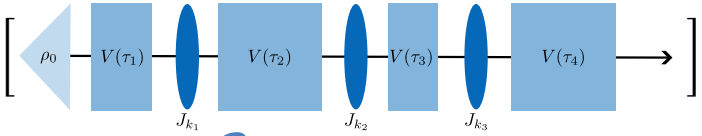
Single qubit, two jump operators



$$L_- = \sqrt{\gamma(\bar{n}+1)}\sigma_-$$

$$L_+ = \sqrt{\gamma\bar{n}}\sigma_+$$

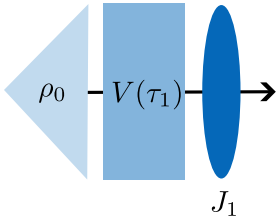
Renewal processes

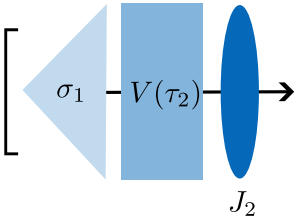
$Pr(\omega_{1:N}) \propto \mathrm{Tr}\Big[$ 

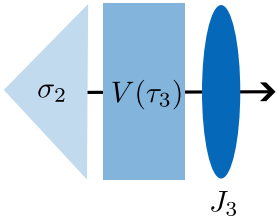
$\Big]$

$\mathscr{M} = 1$ process!

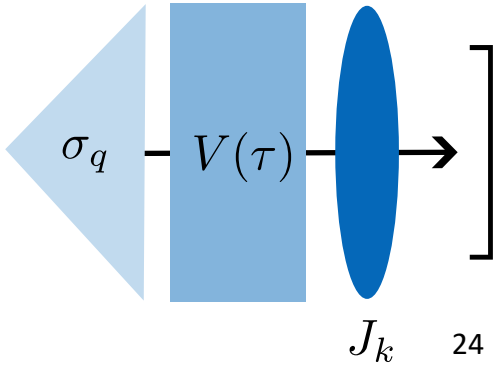
$$\Pr(\omega_{1:N}) = W(\tau_N, k_N \,|\, k_{n-1}) \ldots W(\tau_1, k_1 \,|\, k_0)$$

$\mathrm{Tr}\Big[$ 

$\Big] \times \mathrm{Tr}\Big[$ 

$\Big] \times \mathrm{Tr}\Big[$ 

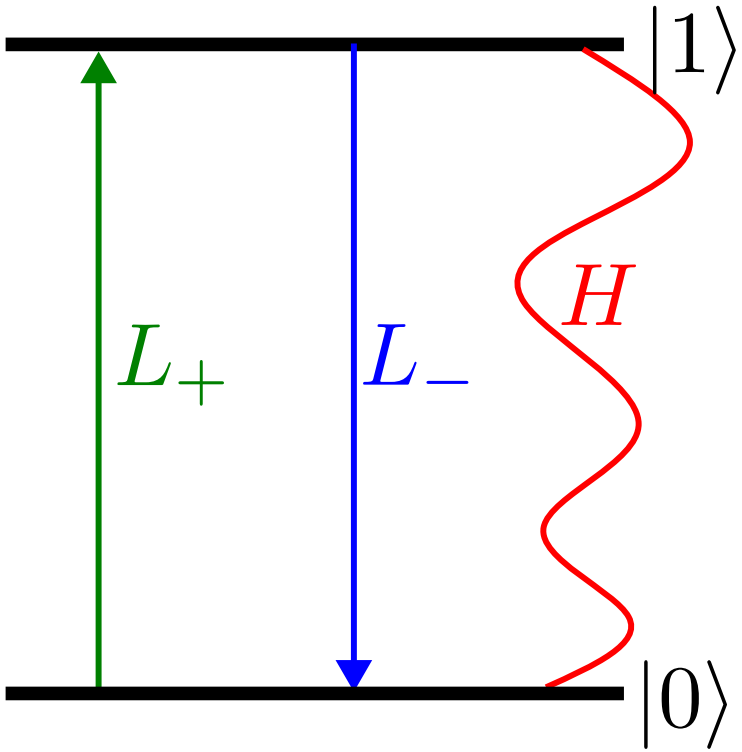
$\Big]$

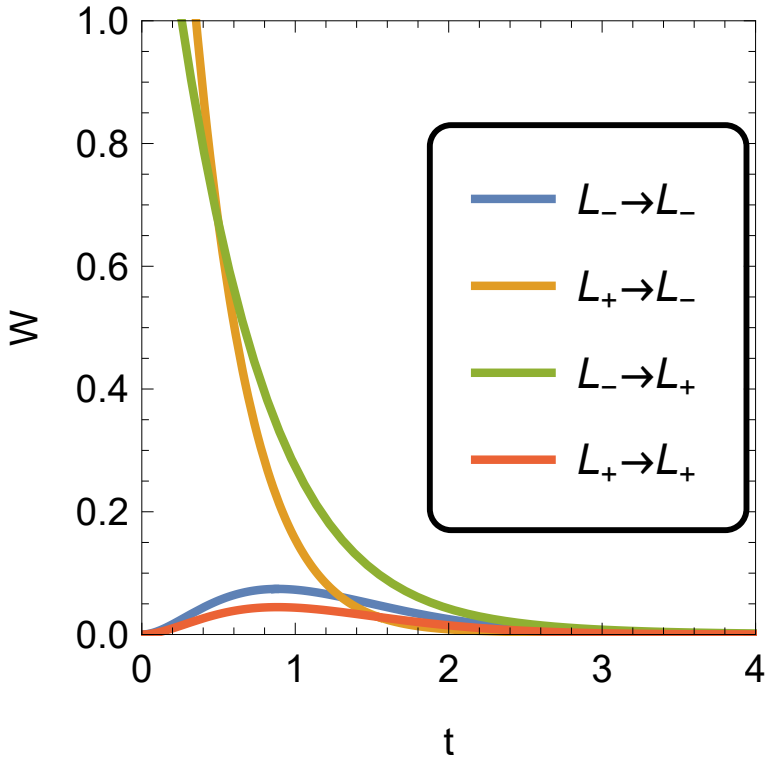
$$W(k, \tau \,|\, q) = \mathrm{Tr}\left[\mathscr{J}_k e^{\mathscr{L}_0 \tau} \sigma_q\right] = \mathrm{Tr}\Big[$$ 

$\Big]$

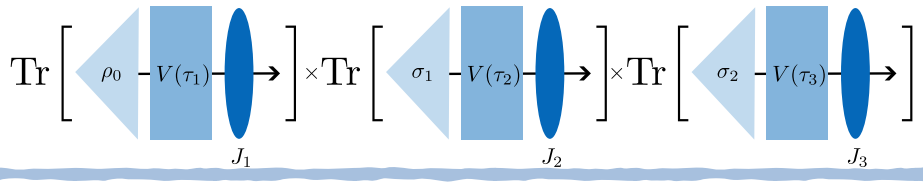
Renewal processes

$$W(\tau, k \,|\, q) = \mathrm{Tr}\Big[\sigma_q \; V(\tau) \; J_k \; \rightarrow\Big]$$





Renewal processes

$\Pr(\omega_{1:N}) =$ 

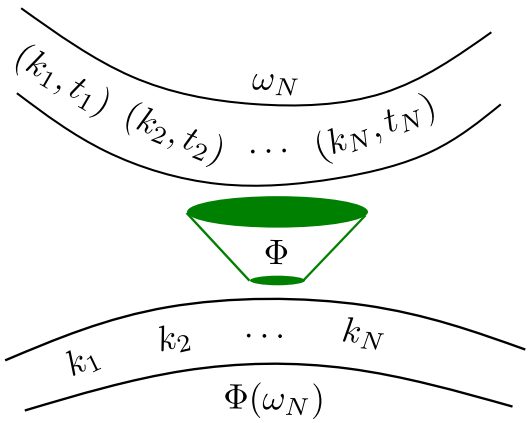
$$\mathbb{E}\left[\left(\hat{\theta}-\theta\right)^2\right] \geq \frac{1}{NF_{1:N}(\theta)} \approx \frac{1}{NF_{2|1}(\theta)}$$

$$F_{2|1}(\theta) = -\sum_{k,q} p_q \int_0^\infty d\tau W(\tau, k\,|\,q)\left(\frac{\partial^2}{\partial\theta^2}\ln W(\tau, k\,|\,q)\right)$$

$$p_q := \frac{\mathrm{Tr}\left[\mathcal{J}_q \rho_{ss}\right]}{\sum_j \mathrm{Tr}\left[\mathcal{J}_j \rho_{ss}\right]}$$

FI for channels and times

$$F_{1:N}(\theta) = F^{\mathsf{ch}}_{1:N}(\theta) + F^{\mathsf{times}\,|\,\mathsf{ch}}_{1:N}(\theta)$$



$$F^{\mathsf{ch}}_{1:N}(\theta) = N \sum_{k,q\in\mathbb{M}} p(k\,|\,q)p_q \left(\partial_\theta \ln p(k\,|\,q)\right)^2$$

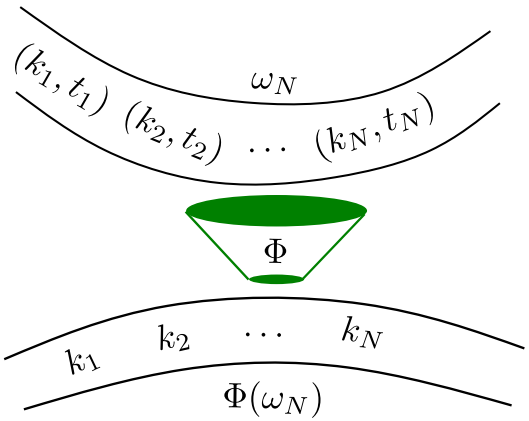
$$F^{\mathsf{times}\,|\,\mathsf{ch}}_{1:N}(\theta) = N \sum_{k,q\in\mathbb{M}} p(k\,|\,q)p_q \int_0^\infty d\tau \frac{[\partial_\theta W(\tau\,|\,k,q)]^2}{W(\tau\,|\,k,q)}$$

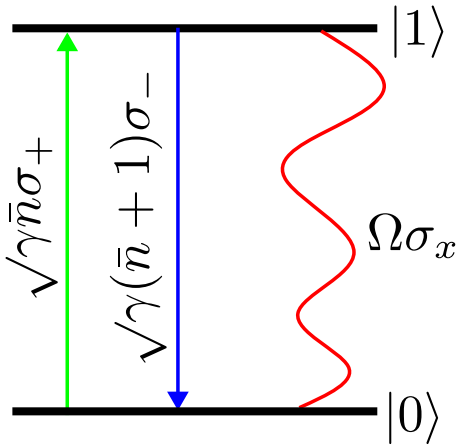
$$W(\tau\,|\,k,q) = \frac{W(\tau,k\,|\,q)}{p(k\,|\,q)} \qquad p(k\,|\,q) = \int_0^\infty W(\tau,k\,|\,q) = -\,\mathsf{Tr}\left[\mathscr{J}_k \mathscr{L}_0^{-1}\sigma_q\right]$$

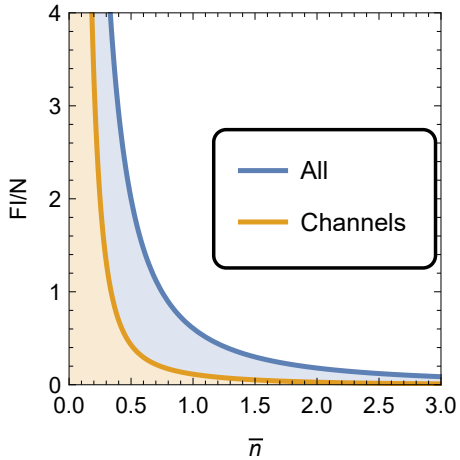
FI for channels and times

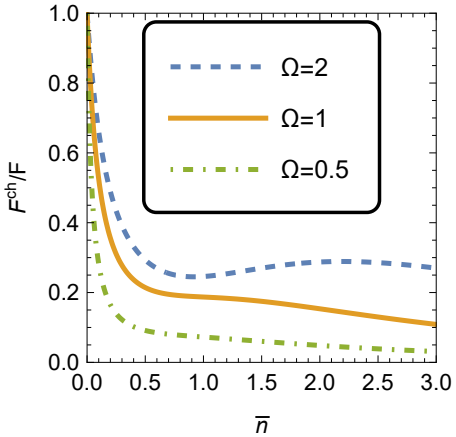
Information in the **jump times** vs information in the **jump channels**.

$$F_{1:N}(\theta) = F^{\text{ch}}_{1:N}(\theta) + F^{\text{times}|\text{ch}}_{1:N}(\theta)$$





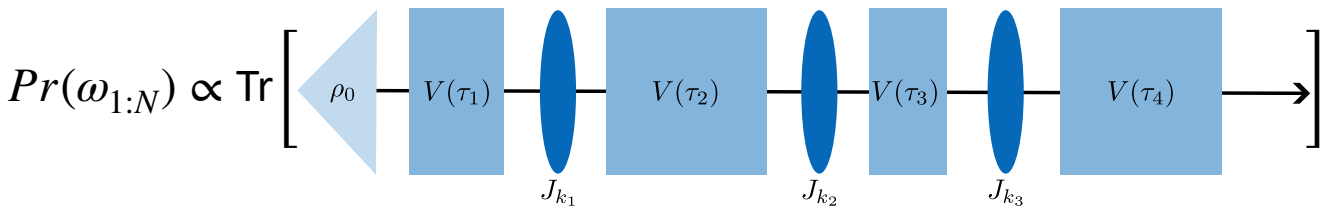




Take-home message #2

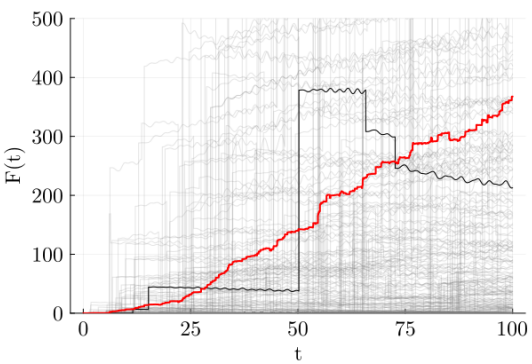
- Renewal processes — reset memory after jump.
- $\mathscr{M} = 1$
- Analytical FI rate
- Partial monitoring / imperfect detection: renewal property gets lost

Non-renewal processes

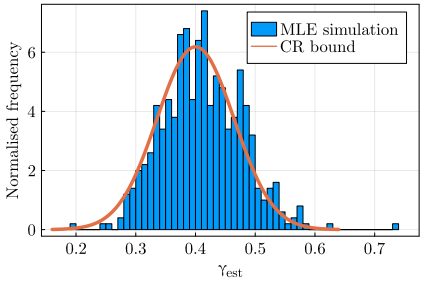


How to do metrology on this measurement record? Two issues:

How to compute the Fisher information?



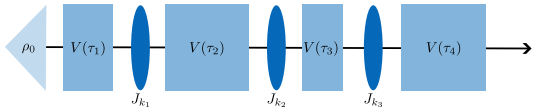
How to actually perform the estimation?



arXiv: 2402.06556

Non-renewal: the monitoring operator

Unnormalised conditional state

$\tilde{\rho}_{\omega_{1:N}} =$ 

Probability of a trajectory

$$\Pr\left[\omega_{1:N}\right] = \mathrm{Tr}\left[\tilde{\rho}_{\omega_{1:N}}\right]$$

$$\xi_{\omega_{1:N}} = \frac{\partial_\theta \tilde{\rho}_{\omega_{1:N}}}{\mathrm{Tr}\left[\tilde{\rho}_{\omega_{1:N}}\right]}$$

Monitoring operator

S. Gammelmark et al., PRA 87.3 032115 (2013)
F. Albarelli et al., Quantum 2 110 (2018)

Non-renewal: the monitoring operator

$$F_{1:N}(\theta) = \mathbb{E}_{\omega_{1:N}}\left[\mathrm{Tr}\left(\xi_{\omega_{1:N}}\right)^2\right]$$

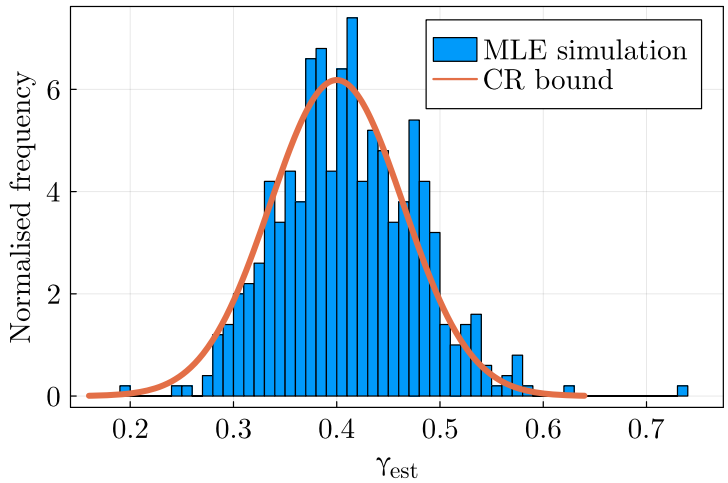
$$\mathrm{Tr}\left[\tilde{\rho}_{\omega_{1:N}}\right] = p(\omega_{1:N}) \qquad \xi_{1:N} = \frac{\partial_\theta \tilde{\rho}_{\omega_{1:N}}}{\mathrm{Tr}[\tilde{\rho}_{\omega_{1:N}}]}$$

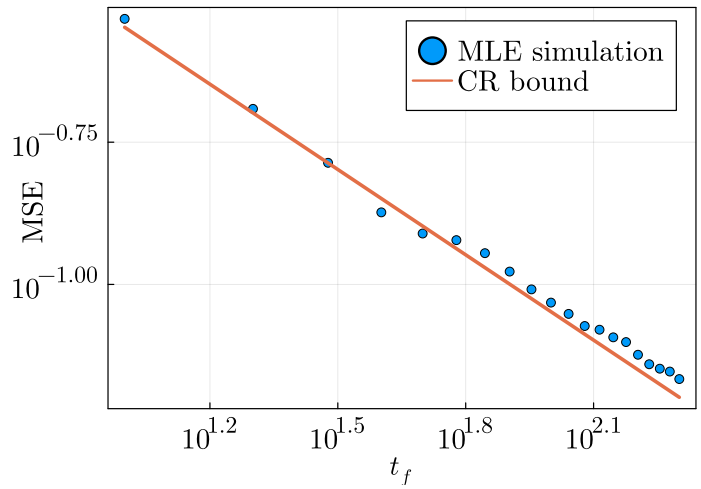
$$\mathrm{Tr}\left[\xi_{\omega_{1:N}}\right]^2 = \frac{\left(\partial_\theta p(\omega_{1:N})\right)^2}{\left(p(\omega_{1:N})\right)^2} = \left(\partial_\theta \ln p(\omega_{1:N})\right)^2 \quad \Rightarrow \quad \mathbb{E}\left[\mathrm{Tr}\left[\xi_{\omega_{1:N}}\right]^2\right] = F_{1:N}(\theta)$$

Numerical computation of the **Fisher information** in the **measurement record**

S. Gammelmark et al., PRA 87.3 032115 (2013)
F. Albarelli et al., Quantum 2 110 (2018)

Maximum Likelihood Estimation





Evolve ξ_t along a trajectory, as if $\theta = \tilde{\theta}$.

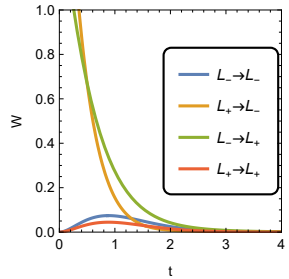
Probability of that trajectory:

$$\ell\left(\tilde{\theta}\right) = p\left[\omega_{1:N} | \tilde{\theta}\right] = \text{Tr}\left[\tilde{\rho}^{\tilde{\theta}}_{\omega_{1:N}}\right]$$

MLE: maximise the probability

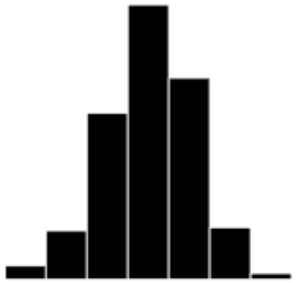
$$\hat{\theta} = \text{argmax}_{\tilde{\theta}} \ell(\theta) = \text{argmin}_{\tilde{\theta}} \left(\text{Tr}\left[\xi^{\tilde{\theta}}_{\omega_{1:N}}\right]\right)^2$$

Non-renewal: Gillespie-Fisher algorithm



Generate WTD for all jumps at current state

Sample from WTD and evolve ρ until jump



Generate jumps distribution

Sample from jumps distribution and evolve ρ and ξ

The numerically heaviest quantities can be **precomputed**

Significant advantage when computing **many trajectories** for relatively **small systems**

M. Radaelli, G.T. Landi, F.C. Binder, Phys. Rev. A **110**, 062212 ('24); M. Radaelli, J.A. Smiga, G.T. Landi, F.C. Binder, arXiv 2402.06556 ('24)

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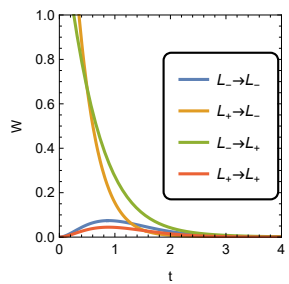

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$$W(\tau \,|\, \rho_{j-1}) = \mathrm{Tr}\left[\mathcal{J} e^{\mathcal{L}_0 \tau} \rho_{j-1}\right]$$

with: $\mathcal{J} = \sum_{k \in \mathbb{M}} \mathcal{J}_k$

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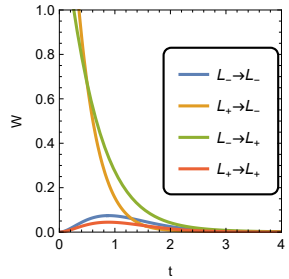

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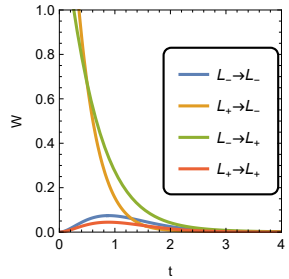

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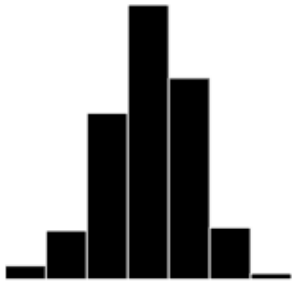

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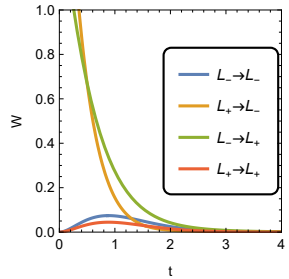

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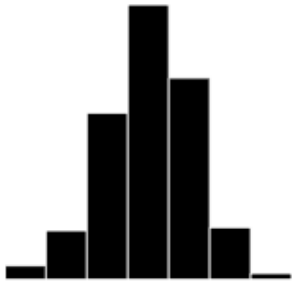

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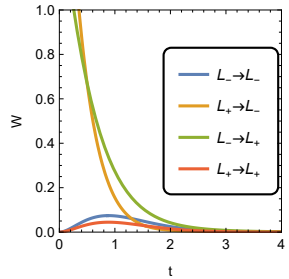
$$\bar{\rho}_j \to \rho_j = \mathcal{J}_{k_j}\bar{\rho}_j/\mathrm{Tr}[\,\circ\,]$$

$$\mathcal{M}_{x_j} = \mathcal{J}_{k_j}e^{\mathcal{L}_0 T_j}$$

$$\rho_j = \mathcal{M}_{x_j}\rho_{j-1}/\mathrm{Tr}[\,\circ\,]$$

$$\xi_j = \frac{\partial_\theta\left(\mathcal{M}_{x_j}\right)\rho_{j-1} + \mathcal{M}_{x_j}\xi_{j-1}}{\mathrm{Tr}(\mathcal{M}_{x_j}\rho_{j-1})}$$

Non-renewal: Gillespie-Fisher algorithm



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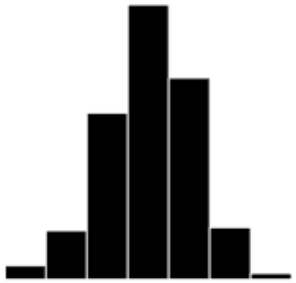

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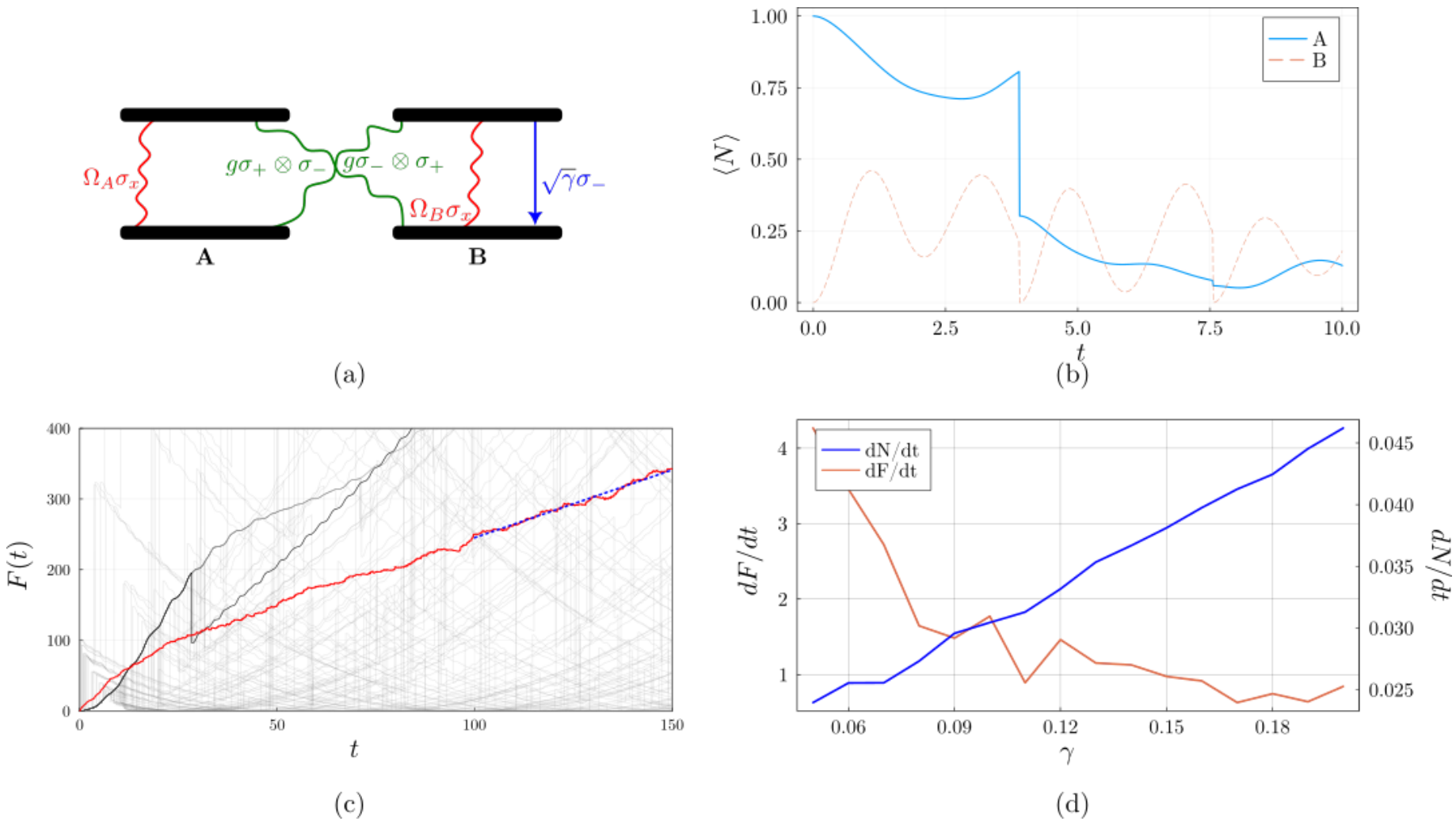

M. Radaelli, J.A. Smiga, G.T. Landi, F.C. Binder, arXiv 2402.06556 ('24)

Fisher information rate

t_f-ensemble -> discretise time: $x_{1:T} = x_1 x_2 \ldots x_T$

$$F(X_{1:T+1}) = F(X_{1:T}) + \underbrace{F(X_{T+1} \,|\, X_{1:T})}_{dF}$$

(chain rule for the FI)

In the limit $dt \to 0$:

$$\boxed{\frac{dF}{dt} = \mathbb{E} \sum_k \frac{1}{I_T^k} \left(\frac{\partial}{\partial \theta} I_T^k \right)^2}$$

where $I_T^k = \mathrm{Tr}\left[L_k^\dagger L_k \rho_t^{(c)} \right]$ is the **stochastic current**.

Radaelli, Landi, Modi, Binder, *New J. Phys.* 25 053037 (2023)
M. Radaelli, J.A. Smiga, G.T. Landi, F.C. Binder, arXiv 2402.06556 (2024)

Take-home message #3

- Non-renewal — $\mathscr{M} = \infty$
- But: numerically tractable (-> monitoring operator)
- FI asymptotically linear with time

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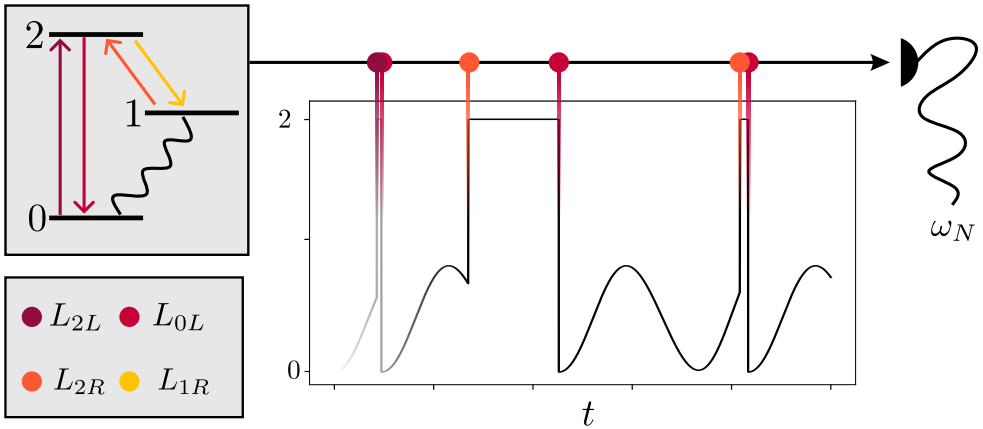

M. Radaelli, G.T. Landi, K. Modi, F.C. Binder. *New J. Phys.* **25** 053037 ('23)
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J.A. Smiga, M. Radaelli, F.C. Binder, G.T. Landi, Phys. Rev. Res. **5** 053037 ('23)

Collborators:
Marco Radaelli (Trinity), Joseph Smiga & Gabriel Landi (Rochester),
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see also:
Marco Radaelli's poster
& talk (Tue, 4 Feb, 4:10pm)

M. Radaelli, G.T. Landi, K. Modi, F.C. Binder. *New J. Phys.* **25** 053037 ('23)
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Mark Mitchison *Trinity College Dublin*
Juliette Monsel *Chalmers University*
Keiji Saito *Kyoto University*
Susanne Still [tbc] *University of Hawaii at Manoa*

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- **06 DEC 2024** — Abstract submissions open
- **16 JAN 2025** — Conference registrations open
- **17 FEB 2025** — Abstract submissions deadline
- **07 APR 2025** — Notification for contributed talks
- **15 MAY 2025** — Poster submission and **registration deadline**
- **07 JUL 2025**