Quantum Batteries: Extractable works and the role of correlations

Gian Marcello Andolina

Phys. Rev. Lett. 122, 047702 (2019)

NEST

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Supervisors:

M. Polini

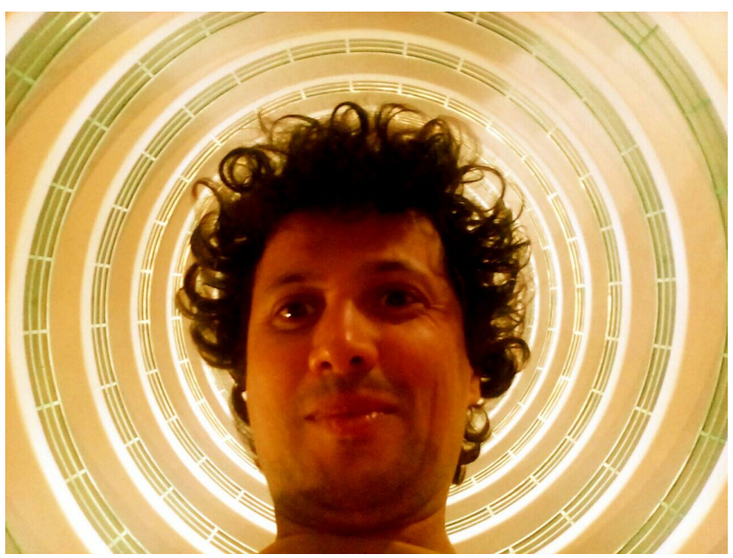
V. Giovannetti

Collaborators:

M. Keck

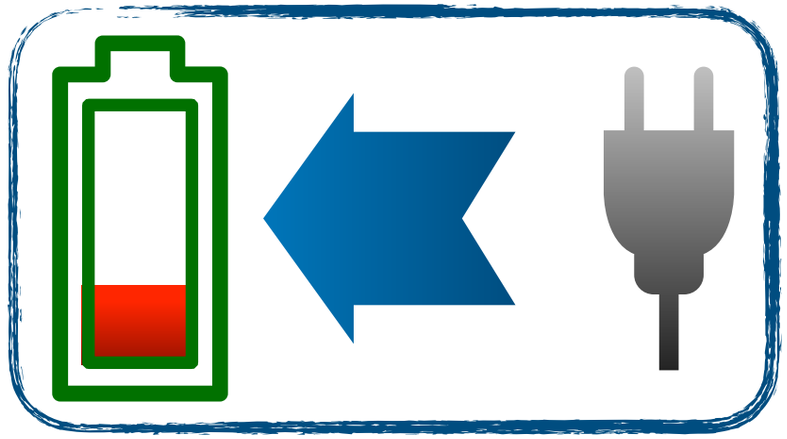
A. Mari

M. Campisi

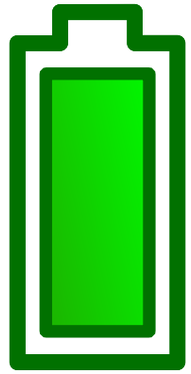


Outline

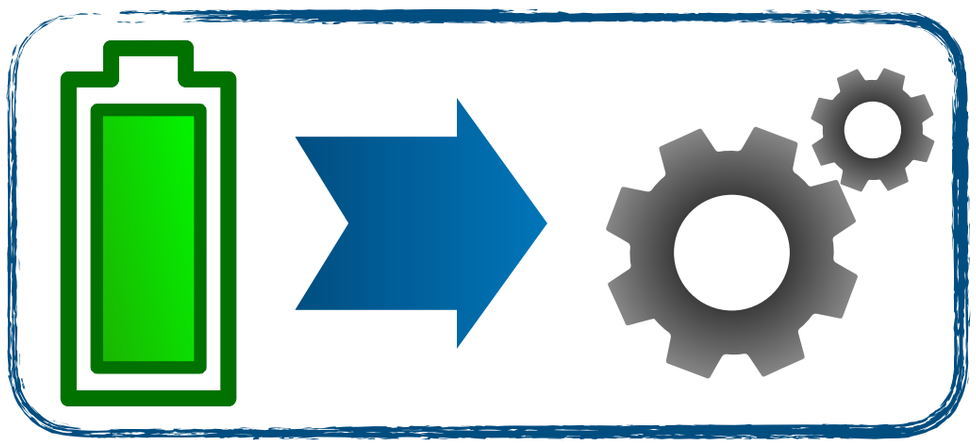
Charging



Storage

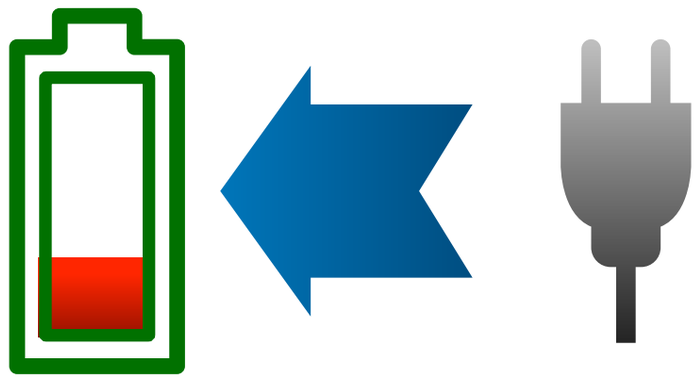


Work Extraction



Charging

Collective Speed-Up

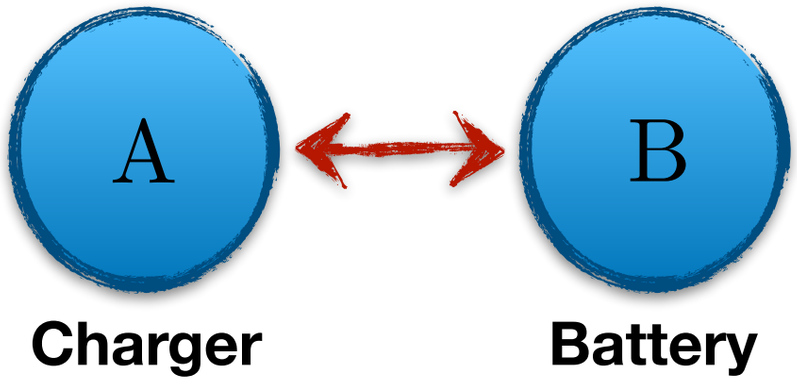


F. C. Binder, S. Vinjanampathy, K. Modi, and J. Goold,
New J. Phys. **17**, 075015 (2015).

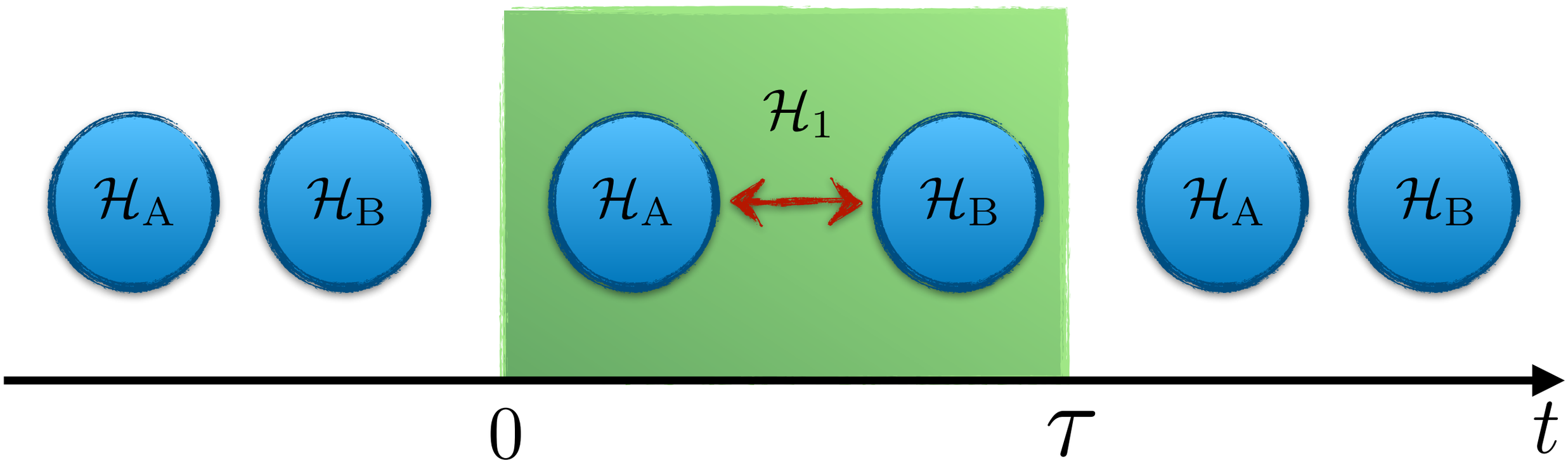
F. Campaioli, F.A. Pollock, F.C. Binder, L.Céleri, J.Goold, S. Vinjanampathy, and K. Modi,
Phys. Rev. Lett. **118**, 150601 (2017)

D. Ferraro, M. Campisi, G.M. Andolina, V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

Charged-mediated energy transfer



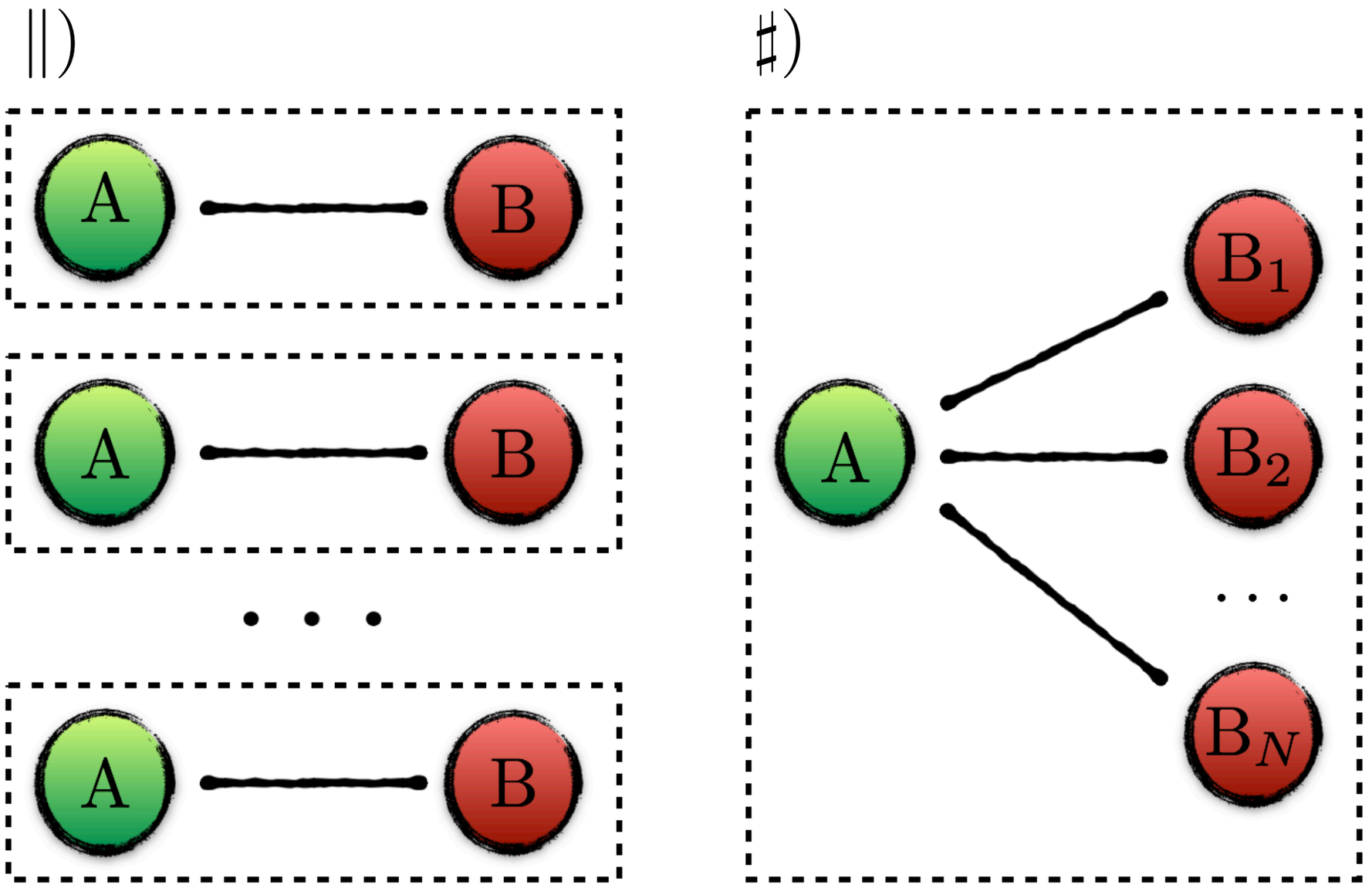
$$\mathcal{H}(t) = \mathcal{H}_{\rm A} + \mathcal{H}_{\rm B} + \lambda(t)\mathcal{H}_1 \qquad \lambda(t) = \mathbb{I}_{[0,\tau]}(t)$$



D. Ferraro, M. Campisi, G.M. Andolina,
V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

G.M. Andolina, D.Farina, A.Mari, V. Pellegrini,
V. Giovannetti and M. Polini
Phys. Rev. B **98**, 205423 (2018)

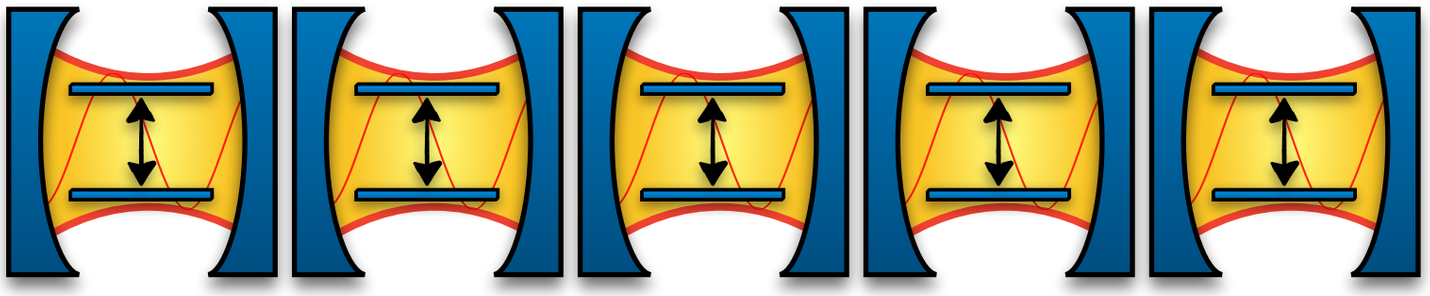
Parallel vs Collective Charging

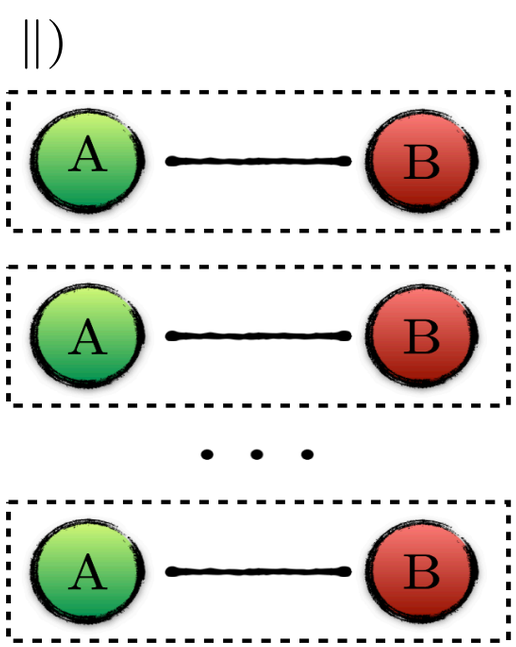


$$E_{\mathrm{A}}^{(\sharp)}(0) = N E_{\mathrm{A}}^{(\|)}(0)$$

Realistic models for cQED

Parallel charging





Rabi Battery

$$\mathcal{H}_{\rm A} = \omega_0 a^\dagger a$$

$$\mathcal{H}_{\rm B} = \omega_0 \sigma^+ \sigma^-$$

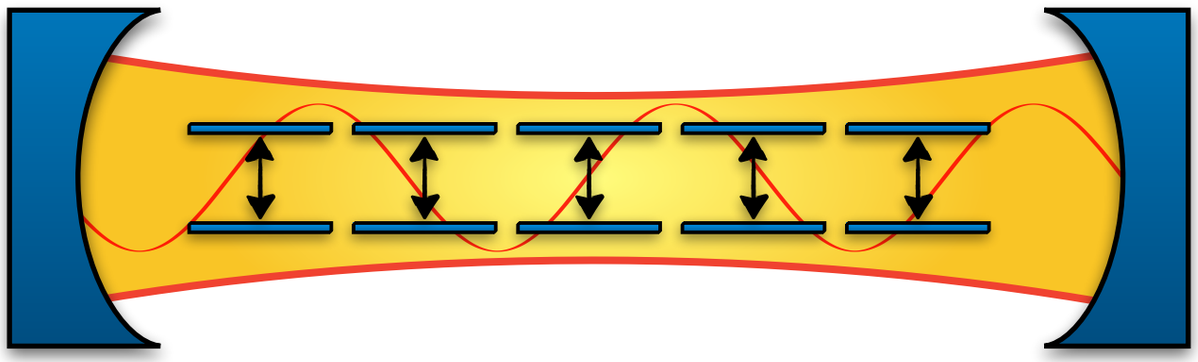
$$\mathcal{H}_1 = g(a + a^\dagger)\sigma^x$$

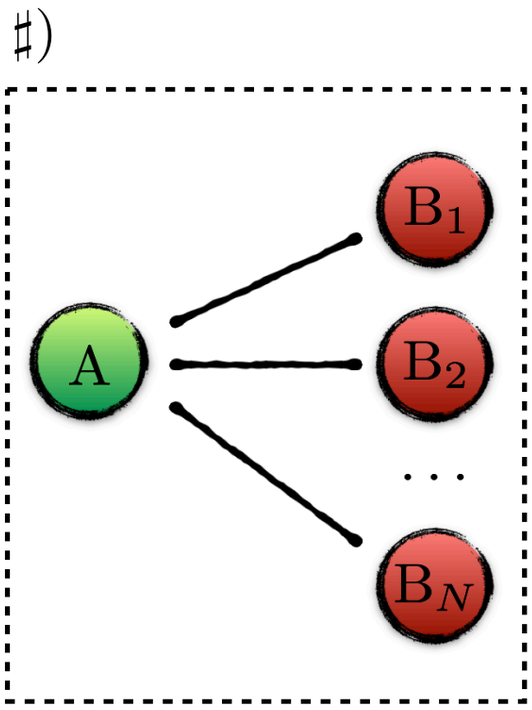
$$|\Psi(0)\rangle = \left[\, |\downarrow\rangle\, |1\rangle \,\right]^{\otimes N}$$

D. Ferraro, M. Campisi, G.M. Andolina, V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

Realistic models for cQED

Collective charging





Dicke Battery

$$\mathcal{H}_{\mathrm{A}} = \omega_0 a^\dagger a$$

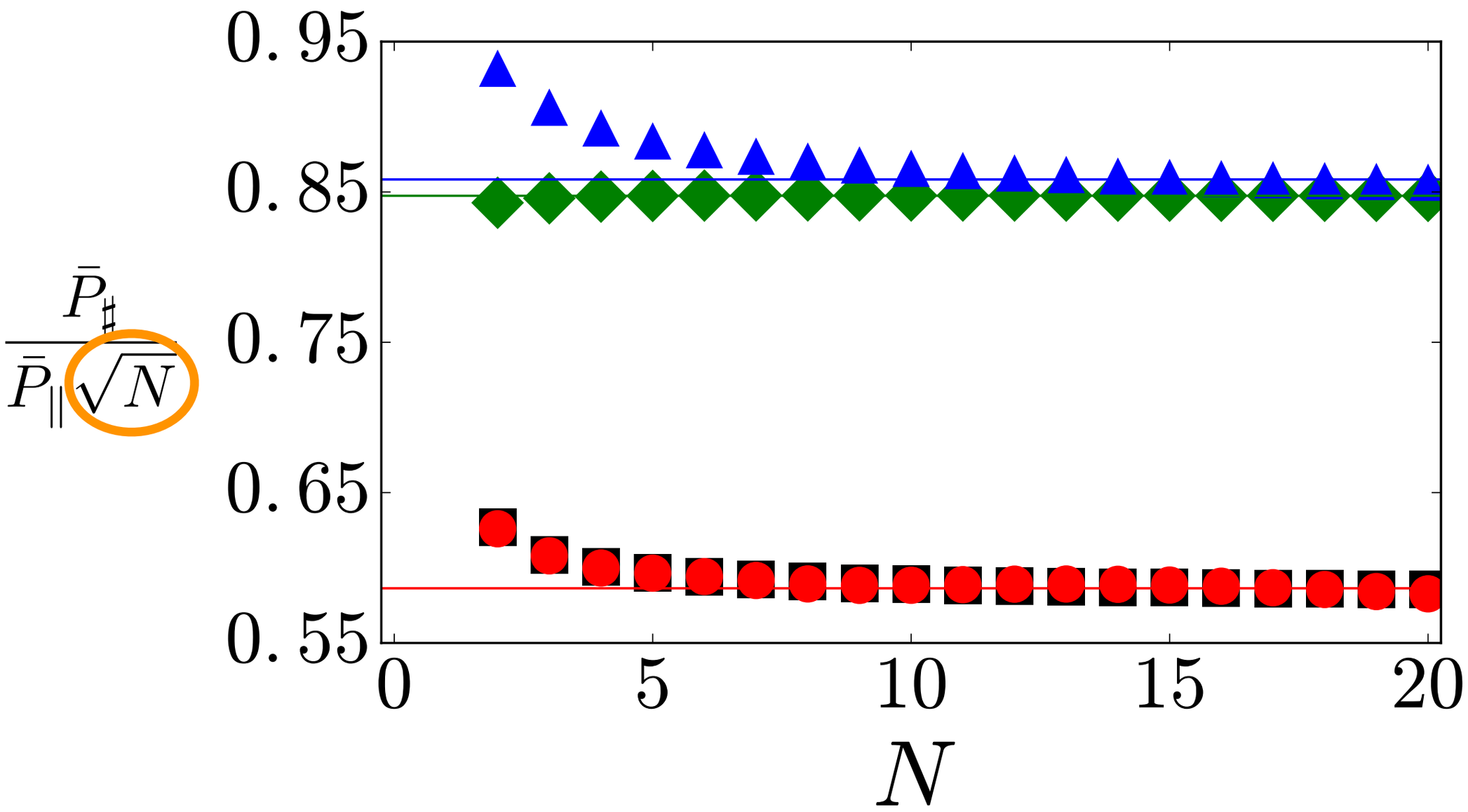
$$\mathcal{H}_{\mathrm{B}} = \sum_i \omega_0 \sigma_i^+ \sigma_i^-$$

$$\mathcal{H}_1 = \sum_i g(a + a^\dagger)\sigma_i^x$$

$$|\Psi(0)\rangle = |\downarrow, \downarrow, \ldots, \downarrow,\rangle \, |N\rangle$$

D. Ferraro, M. Campisi, G.M. Andolina, V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

$\bar{\tau}$ Optimal time

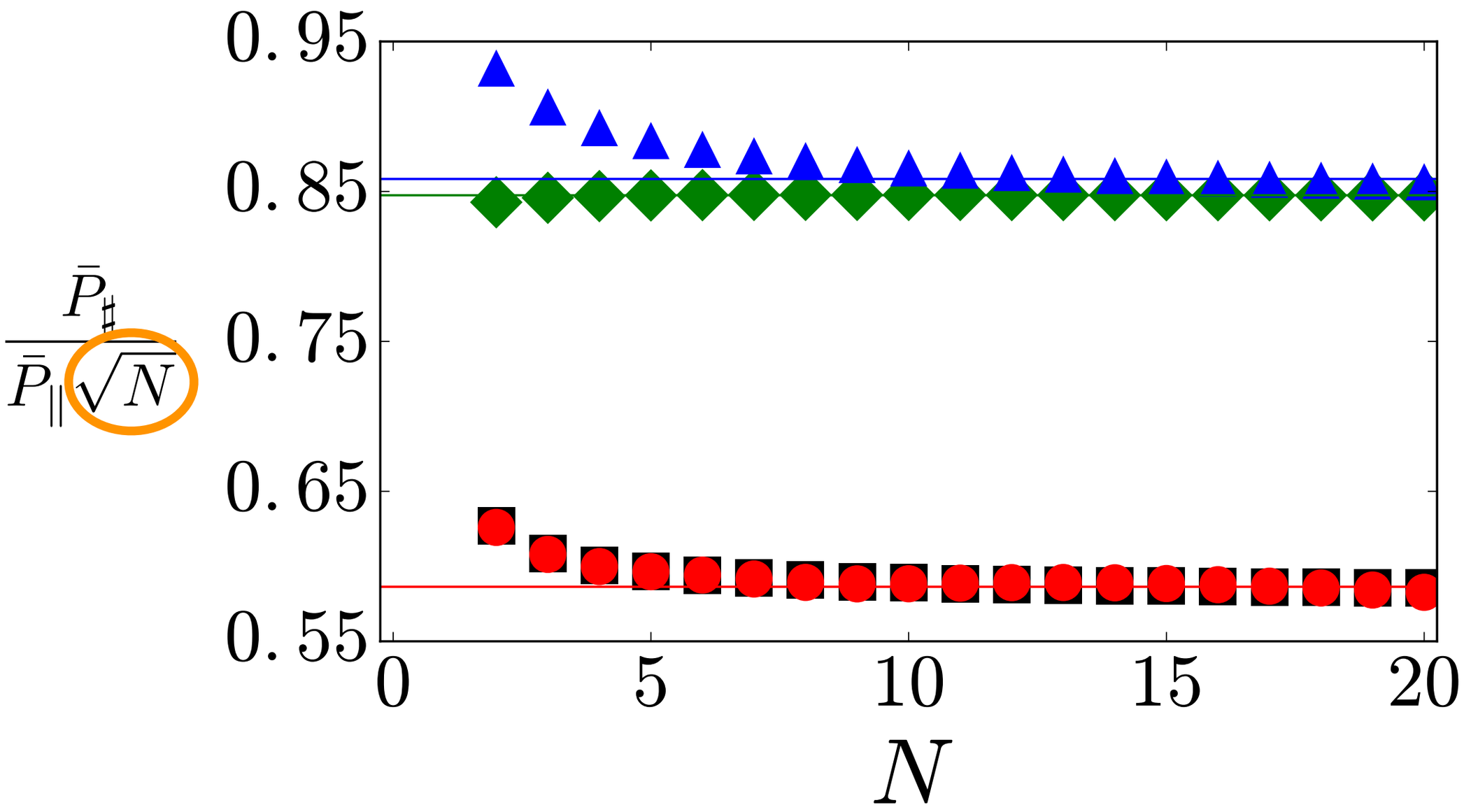


$$P(\tau) = \frac{E(\tau)}{\tau}$$

Collective advantage $\tau_\sharp \sim \dfrac{\tau_\parallel}{\sqrt{N}}$

D. Ferraro, M. Campisi, G.M. Andolina, V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

$\bar{\tau}$ **Optimal time**

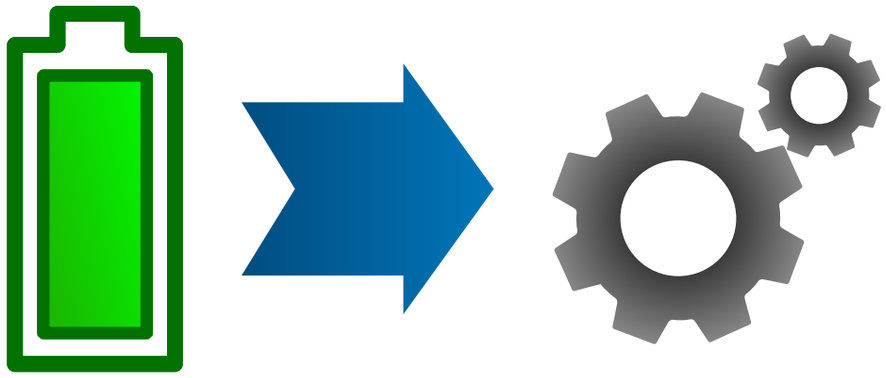


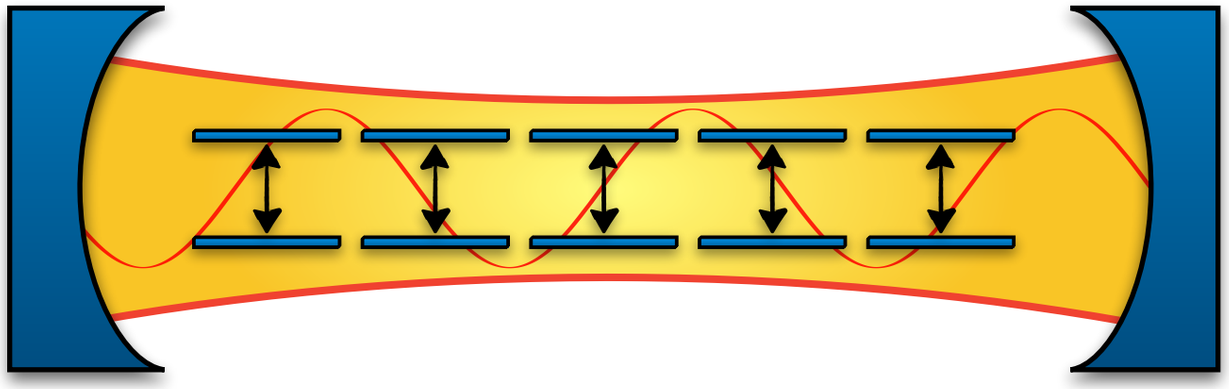
$$P(\tau) = \frac{E(\tau)}{\tau}$$

Collective advantage $\Gamma = \dfrac{\bar{P}^{(\sharp)}}{\bar{P}^{(\parallel)}} \sim \sqrt{N}$

D. Ferraro, M. Campisi, G.M. Andolina, V. Pellegrini, and M. Polini
Phys. Rev. Lett. **120**, 117702 (2018)

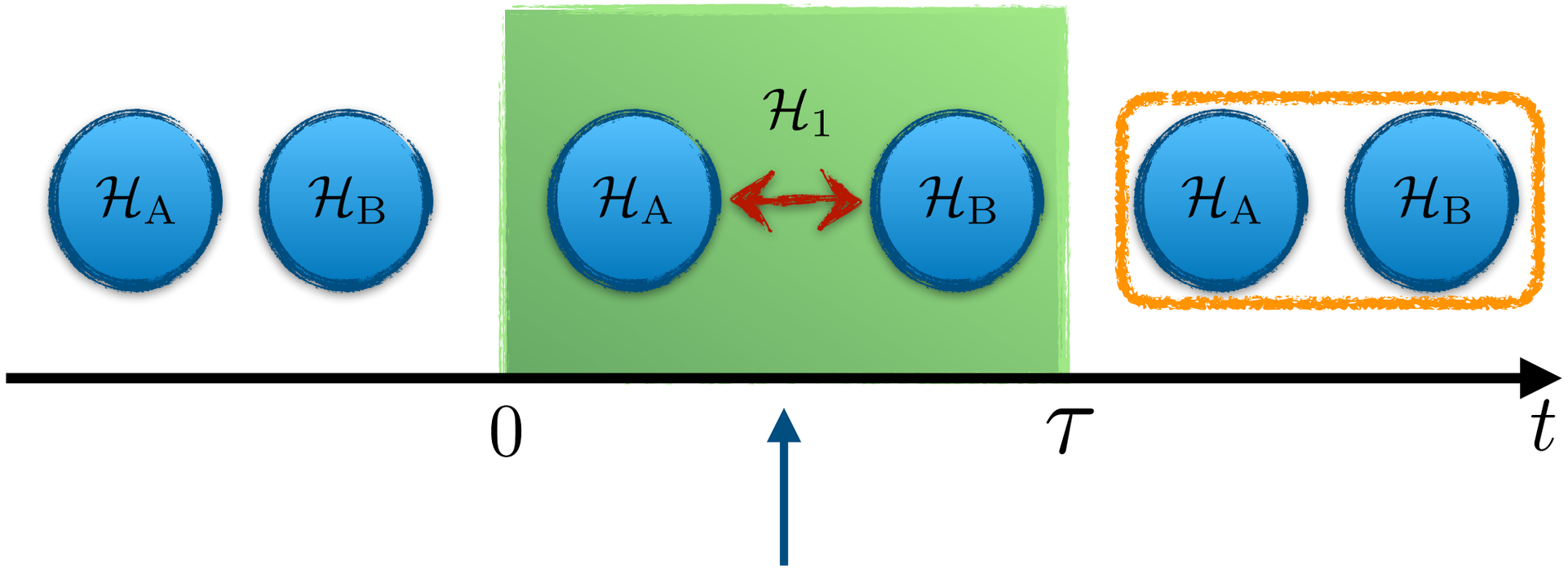
Correlations and work extraction





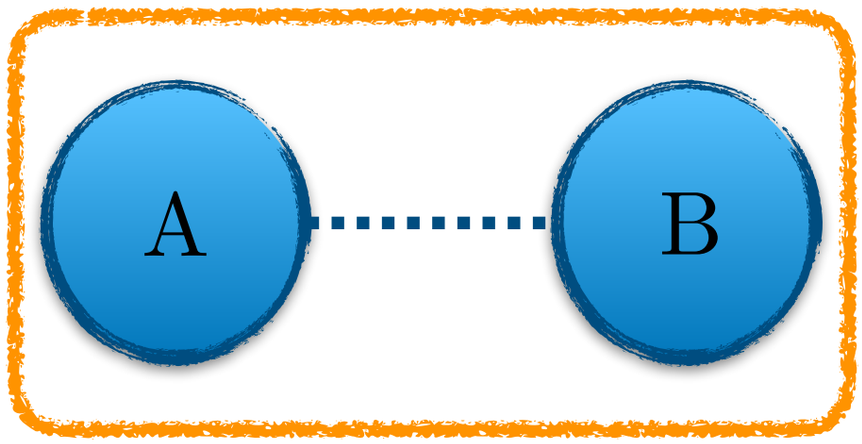
R. Alicki and M. Fannes
Phys. Rev. E **87**, 042123 (2013)

G.M. Andolina, A.Mari, M.Keck, M.Campisi,
M. Polini and V. Giovannetti
Phys. Rev. Lett. **122**, 047702 (2019)

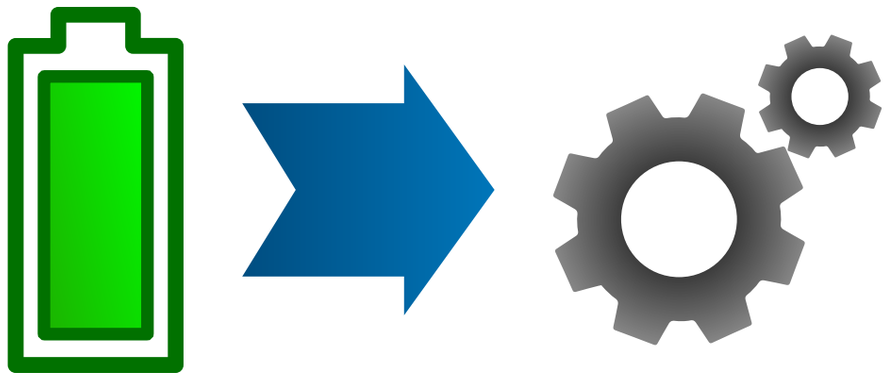


Previous work focused on the speed of the process

During the charging some correlations are created



Ergotropy



$\mathcal{V}(t)$

$$\rho \to U(t^*)\rho U^\dagger(t^*)$$

$$U(t) = \mathcal{T}\{\exp\left[-i\int_0^t dt'(\mathcal{H}_0 + \mathcal{V}(t'))\right]\}$$

$$W = \mathrm{tr}[\rho\mathcal{H}_0] - \mathrm{tr}[U(t^*)\rho U^\dagger(t^*)\mathcal{H}_0]$$

$$\mathcal{E}(\rho) := W_{\max} = \mathrm{tr}[\rho\mathcal{H}_0] - \min_{\mathrm{U}}\ \mathrm{tr}[U\rho U^\dagger\mathcal{H}_0]$$

$$\mathcal{E}(\rho) \leq \Delta F_\beta(\rho) = E(\rho) - E(\omega_\beta) - \frac{1}{\beta}\left[S(\rho) - S(\omega_\beta)\right] \quad \forall\beta$$

R. Alicki and M. Fannes
Phys. Rev. E **87**, 042123 (2013)

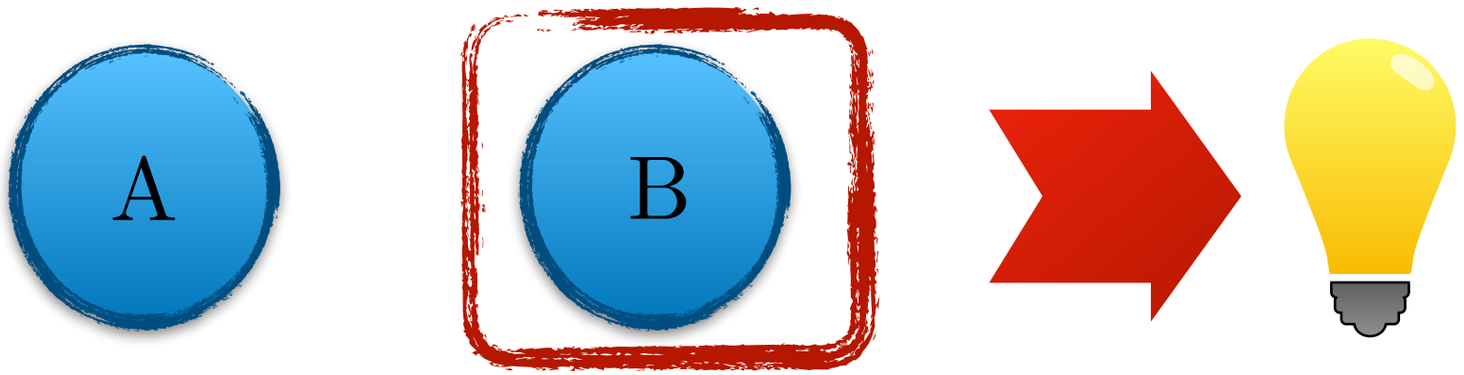
G. Manzano, F. Plastina, R. Zambrini
Phys. Rev. Lett. **121**, 120602 (2018)

After the protocol

$$\rho^{\mathrm{f}}_{\mathrm{AB}} = U^{\dagger}\rho^{\mathrm{i}}_{\mathrm{AB}}U$$

ρ_{AB} **remains pure**

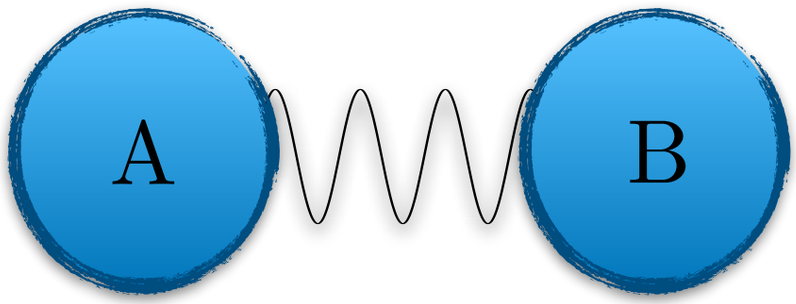
After the protocol



$\mathcal{E}_{\mathrm{B}}(\rho_{\mathrm{B}})$

ρ_{B} **is no longer pure**

Due to correlations established with A



$$\mathcal{E}_{\mathrm{B}}(\rho_{\mathrm{B}}) \neq E_{\mathrm{B}}(\rho_{\mathrm{B}})$$

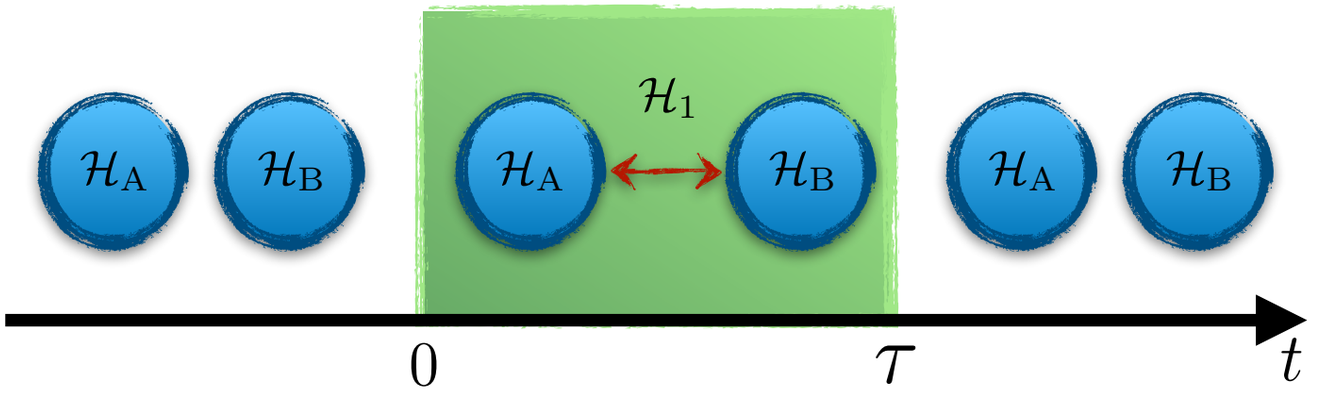
There is energy locked in correlations

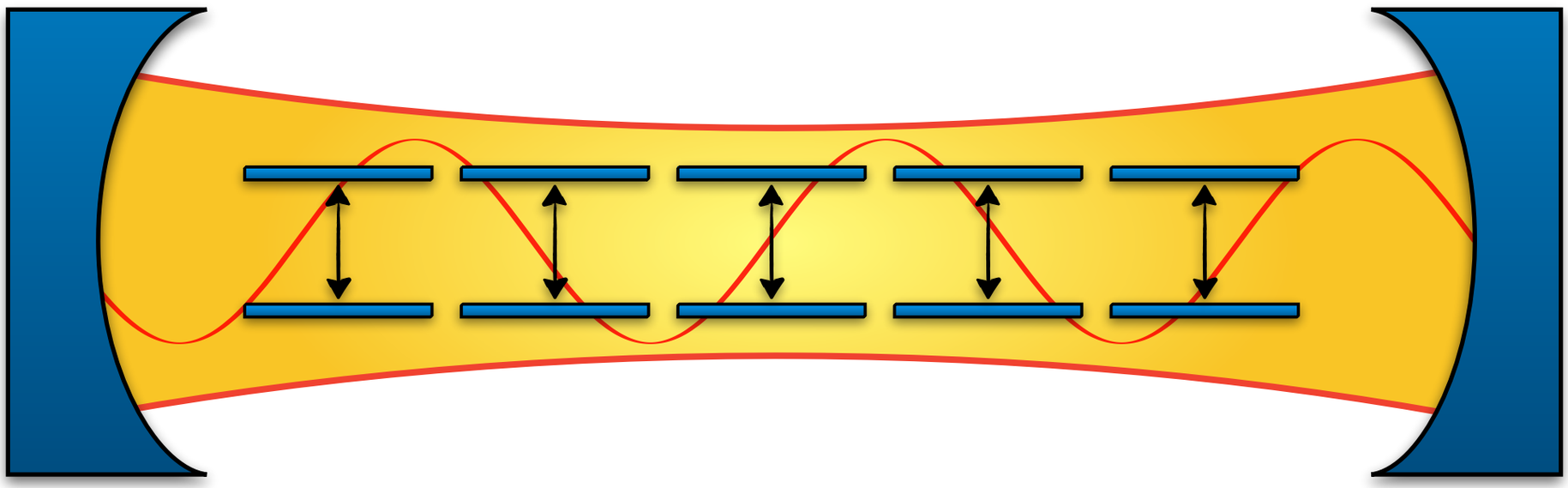
Tavis-Cummings battery

$$\mathcal{H}_{\mathrm{A}} = \omega_0 a^\dagger a$$

$$\mathcal{H}_{\mathrm{B}} = \sum_i \omega_0 \sigma_i^+ \sigma_i^-$$

$$\mathcal{H}_1 = \sum_i g(a\sigma_i^+ + a^\dagger \sigma_i^-)$$





Fock

$$p_n^{(N)} = \delta_{n,N}$$

Coherent

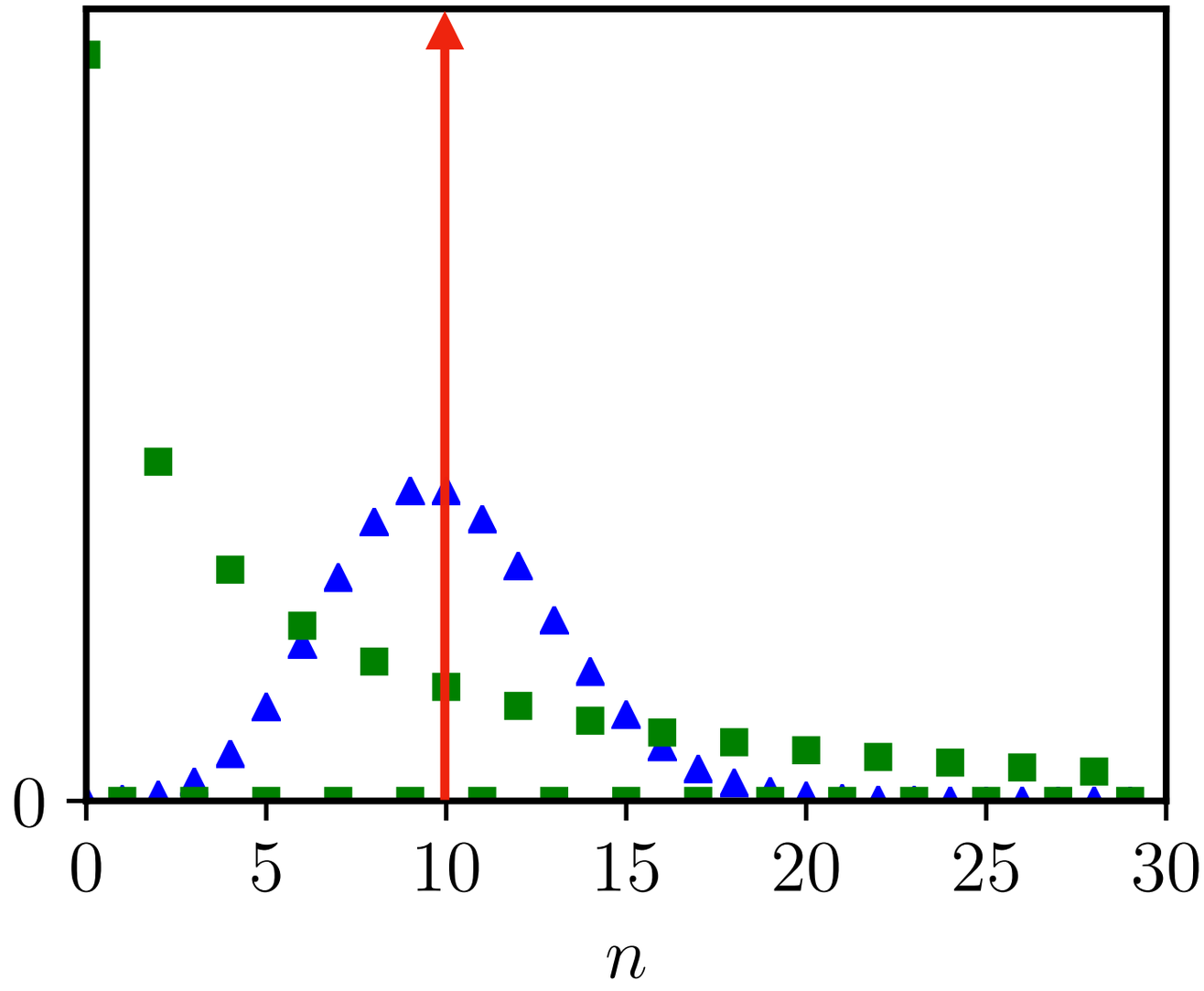
$$p_n^{(N)} = e^{-N} N^n / n!$$

Squeezed vacuum

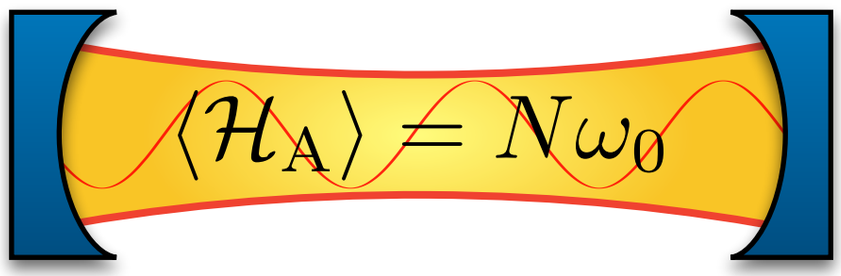
$$p_{2n}^{(N)} = \frac{1}{\cosh(r_N)} \left[\frac{\tanh(r_N)}{2}\right]^{2n} \frac{2n!}{n!^2}$$

$$p_{2n+1}^{(N)} = 0$$

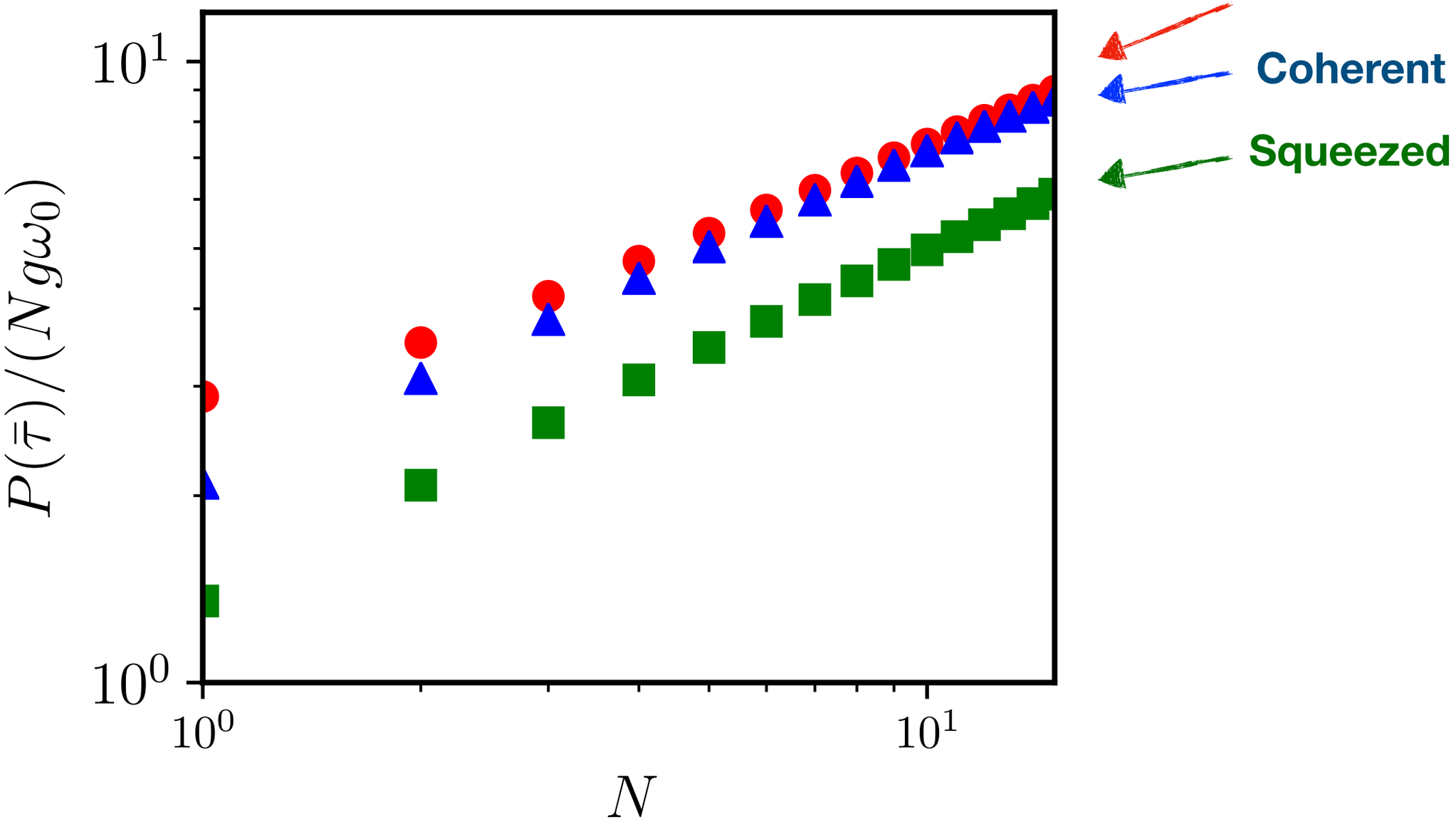
$$r_N = \operatorname{arcsinh}(\sqrt{N})$$

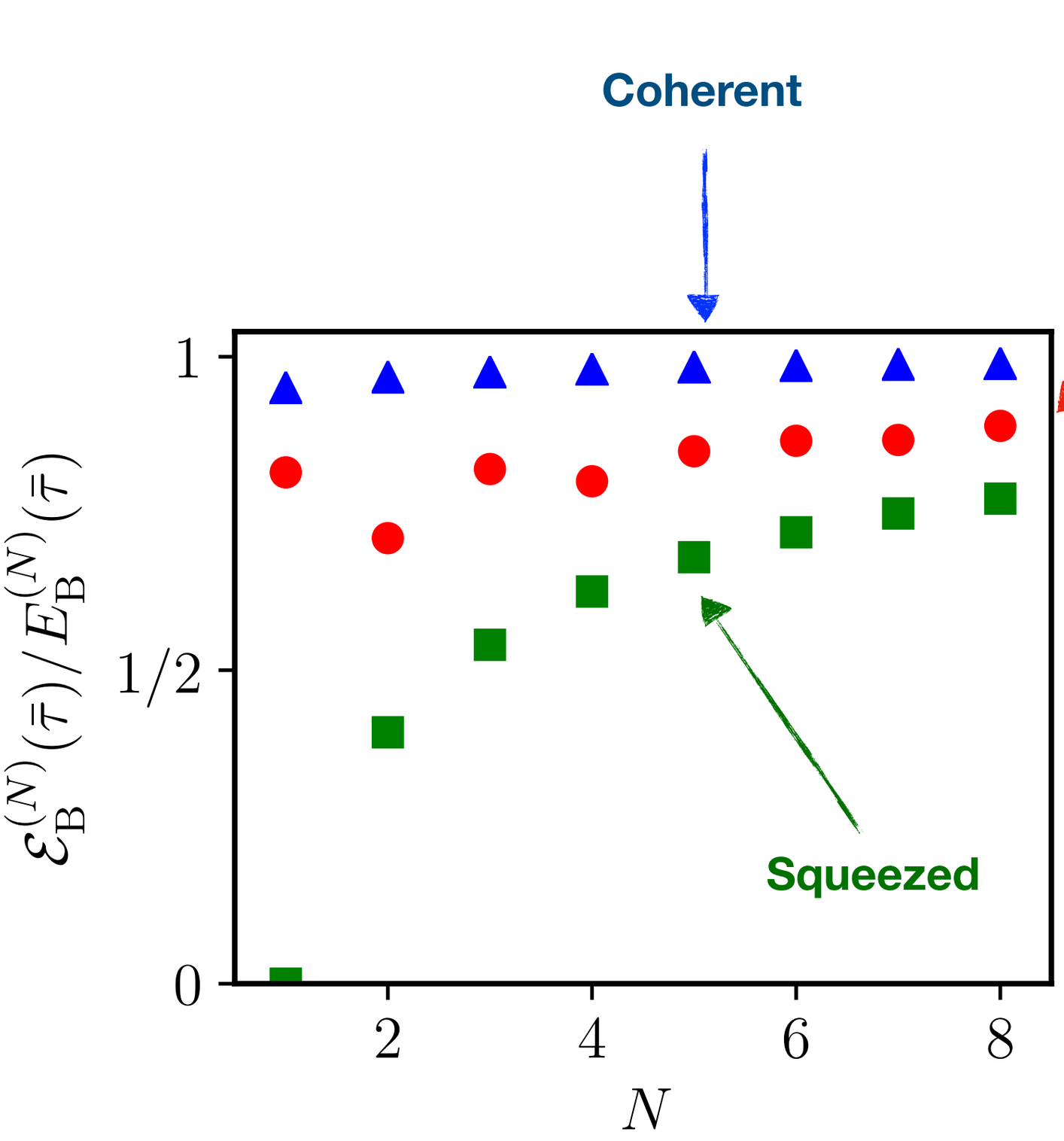


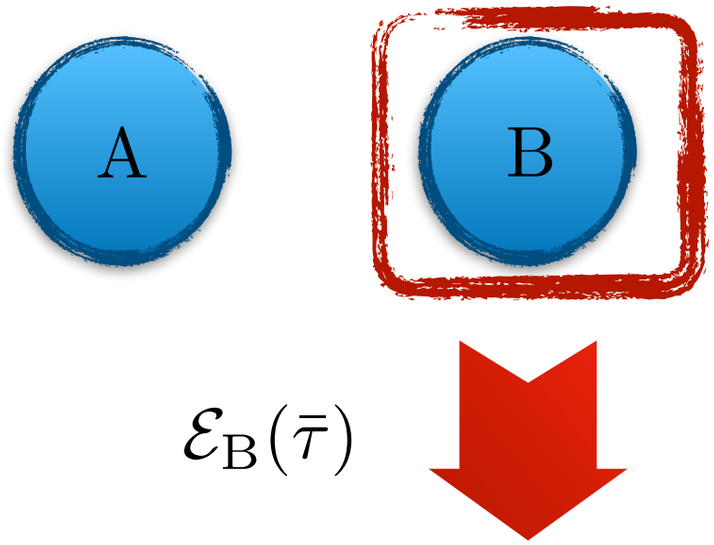
$$|\Psi(0)\rangle = |\downarrow, \downarrow, \ldots, \downarrow\rangle \, |\phi_{\rm ph}\rangle$$



All states share the same collective advantage







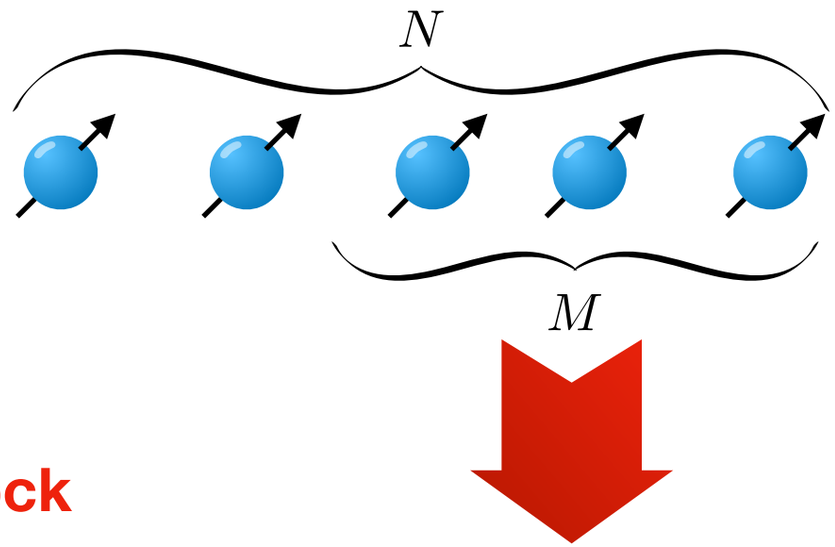
In integrable models:

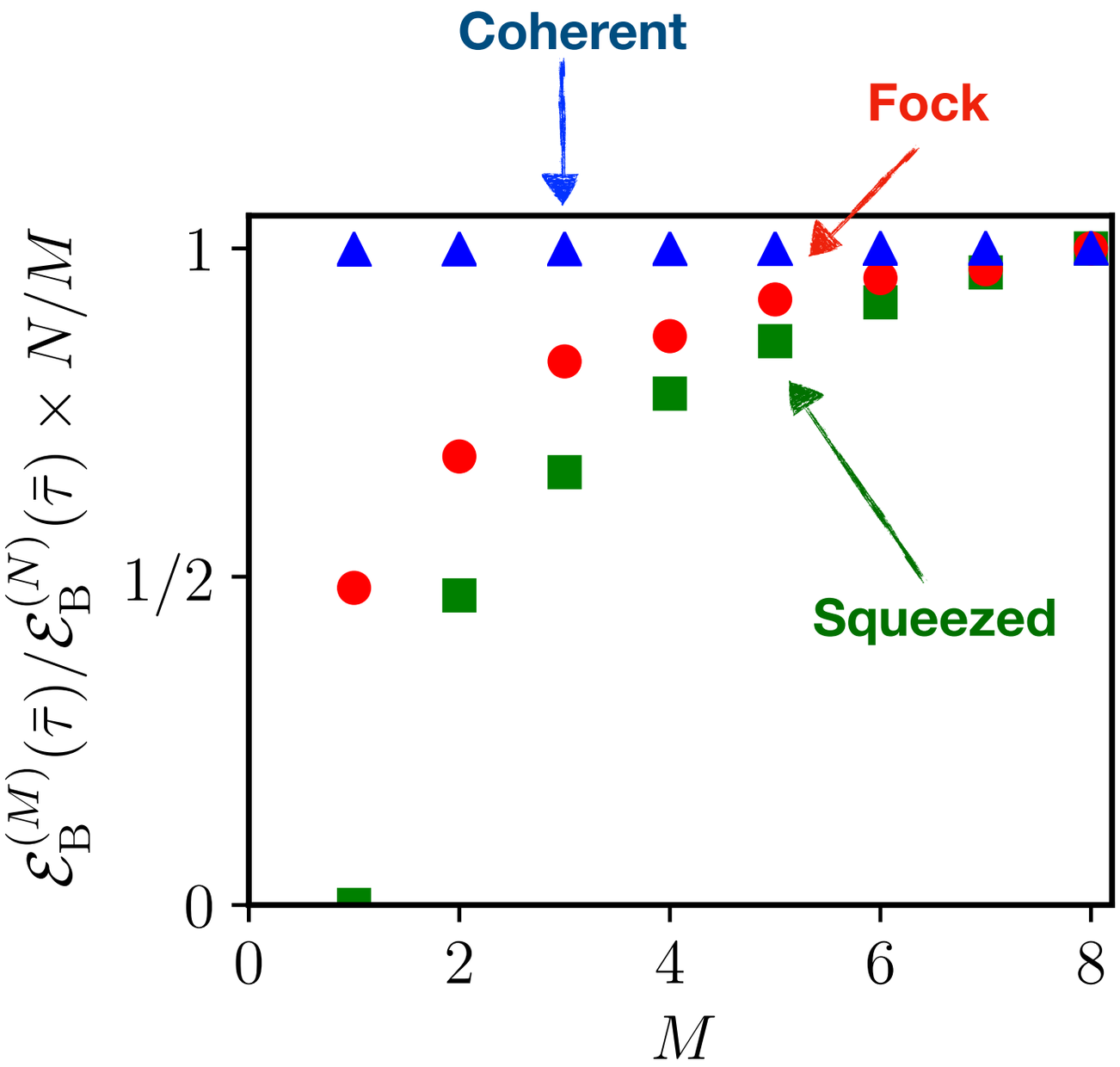
$$N \to \infty \qquad \frac{\mathcal{E}_{\mathrm{B}}^{(N)}}{E_{\mathrm{B}}^{(N)}} \to 1$$

Can be proven analytically

We extract energy from M over the total N qubits

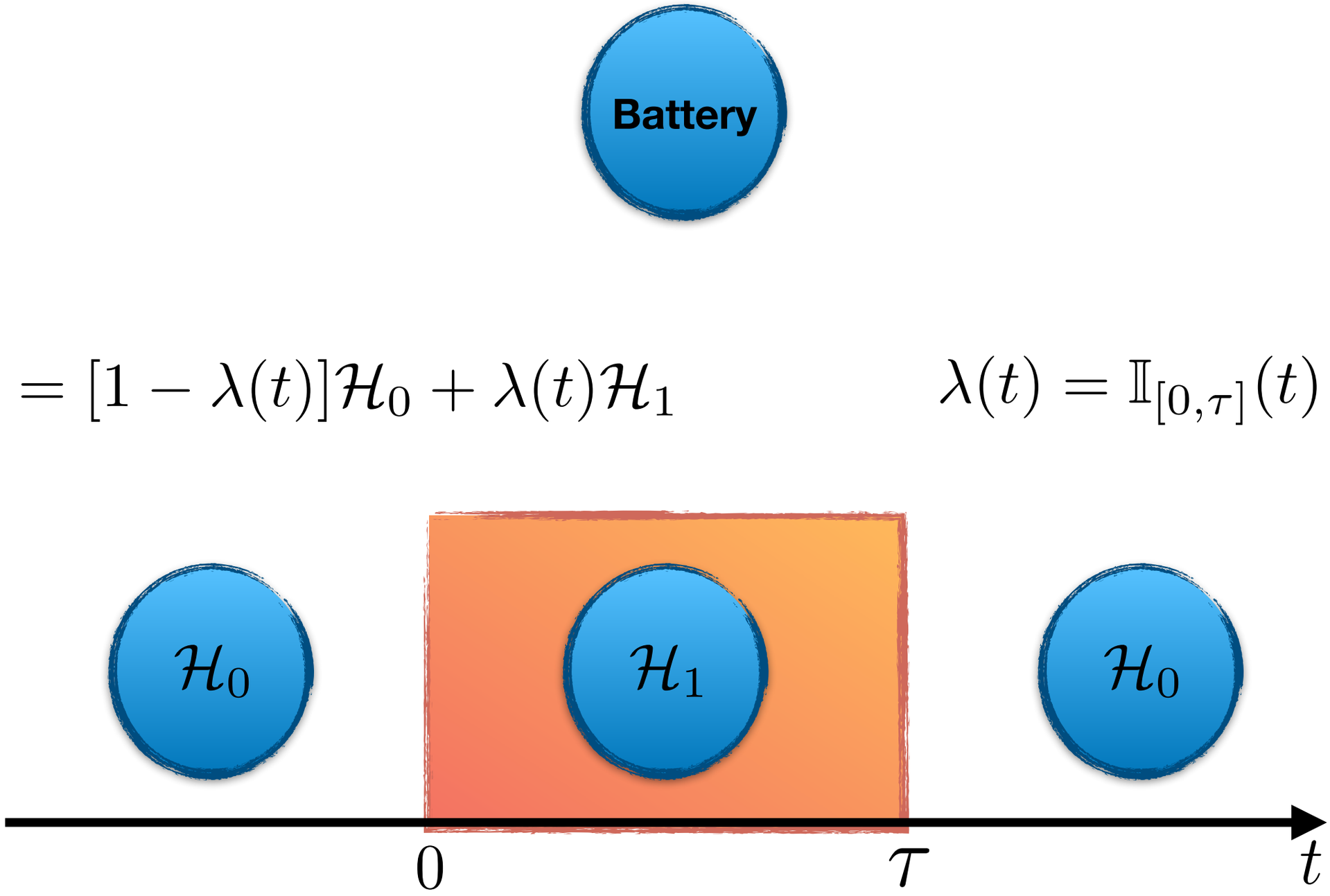
$$N = 8$$





Coherent states are better!

Energy charging via quench



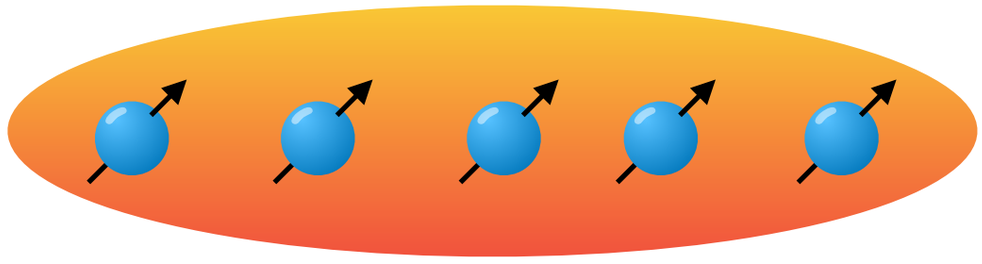
$$\mathcal{H}(t) = [1 - \lambda(t)]\mathcal{H}_0 + \lambda(t)\mathcal{H}_1 \qquad \lambda(t) = \mathbb{I}_{[0,\tau]}(t)$$

T. P. Le, J. Levinsen, K. Modi, M. M. Parish, and F.A. Pollock,
Phys. Rev. **A** 97, 022106 (2018).

D. Rossini, G.M. Andolina and M. Polini,
arXiv:1906.00644

Many-body localized Quantum Battery

Disordered Quantum Ising Chain
Jonas A. Kjäll, Jens H. Bardarson, and Frank Pollmann
Phys. Rev. Lett. **113**, 107204 (2014)



Anderson localized

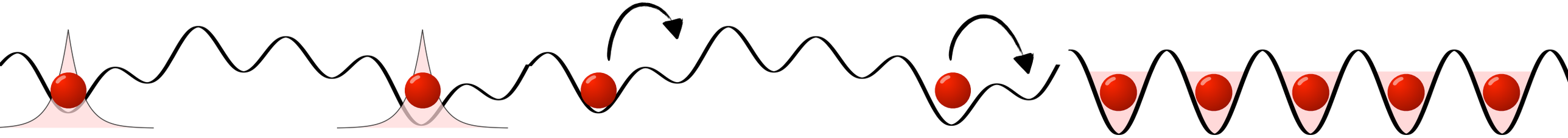
Area law

Many-body localized

Area law (with log-corrections)

Ergodic

Volume law



Not a ground state property!

D.A. Abanin, E. Altman, I. Bloch, and M. Serbyn
Rev. Mod. Phys. **91**, 021001 (2019)

D. Rossini, G.M. Andolina and M. Polini
arXiv:1906.00644

Many-body localized Quantum Battery

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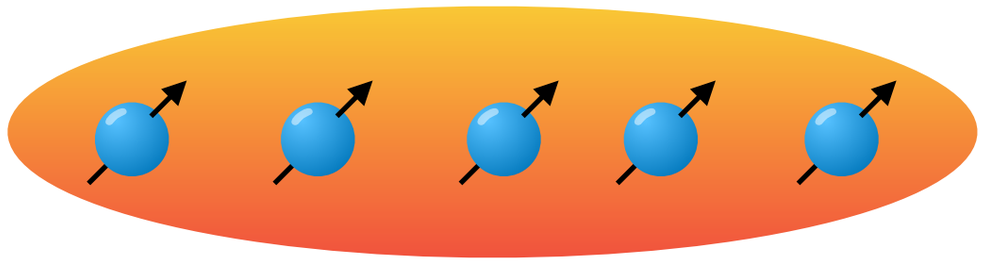
Phys. Rev. Lett. **113**, 107204 (2014)



Anderson localized

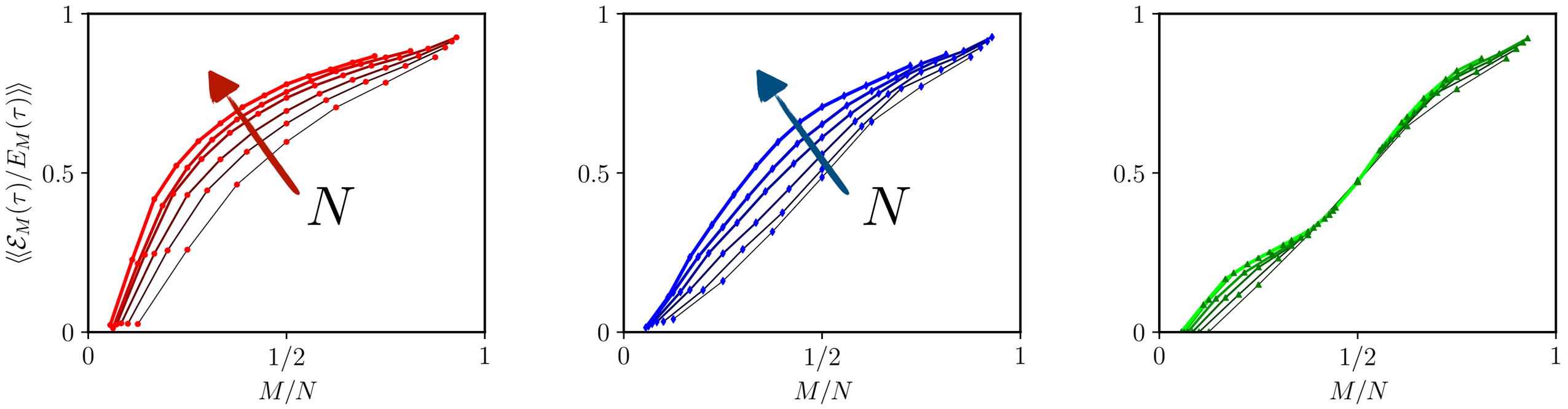
Area law (integrable)

Many-body localized

Area law (with log-corrections)

Ergodic

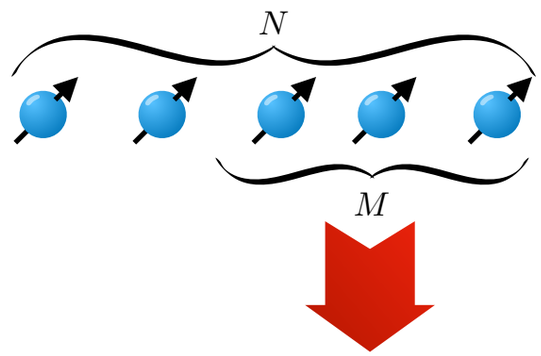
Volume law



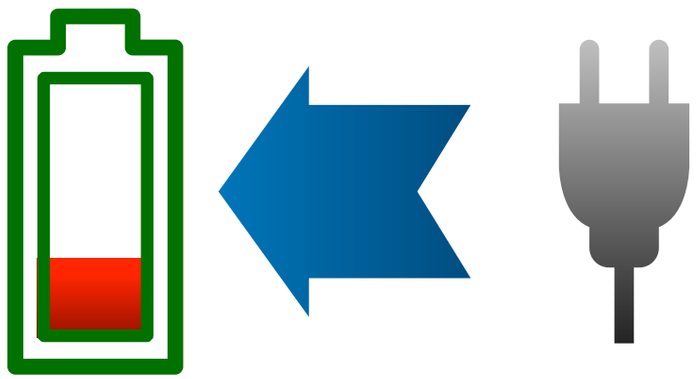
$$\left\langle\left\langle \frac{\mathcal{E}_M(\tau)}{E_M(\tau)} \right\rangle\right\rangle \to 1$$

$$N \to \infty$$

D. Rossini, G.M. Andolina and M. Polini
arXiv:1906.00644

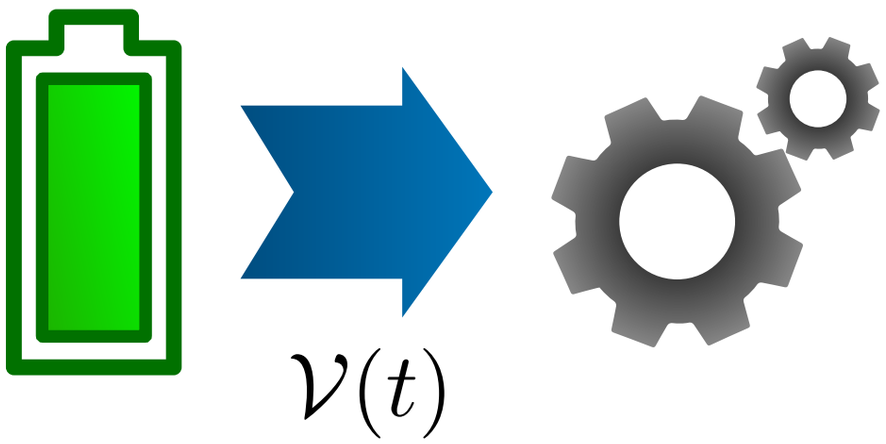


Conclusions



Collective evolution gives an advantage in the power

$$\Gamma \sim \sqrt{N}$$



Coherent states are “optimal” for work extraction

Integrable systems are convenient in the limit $N \to \infty$

Thanks for your attention!