Autonomous Measurement-based Engine

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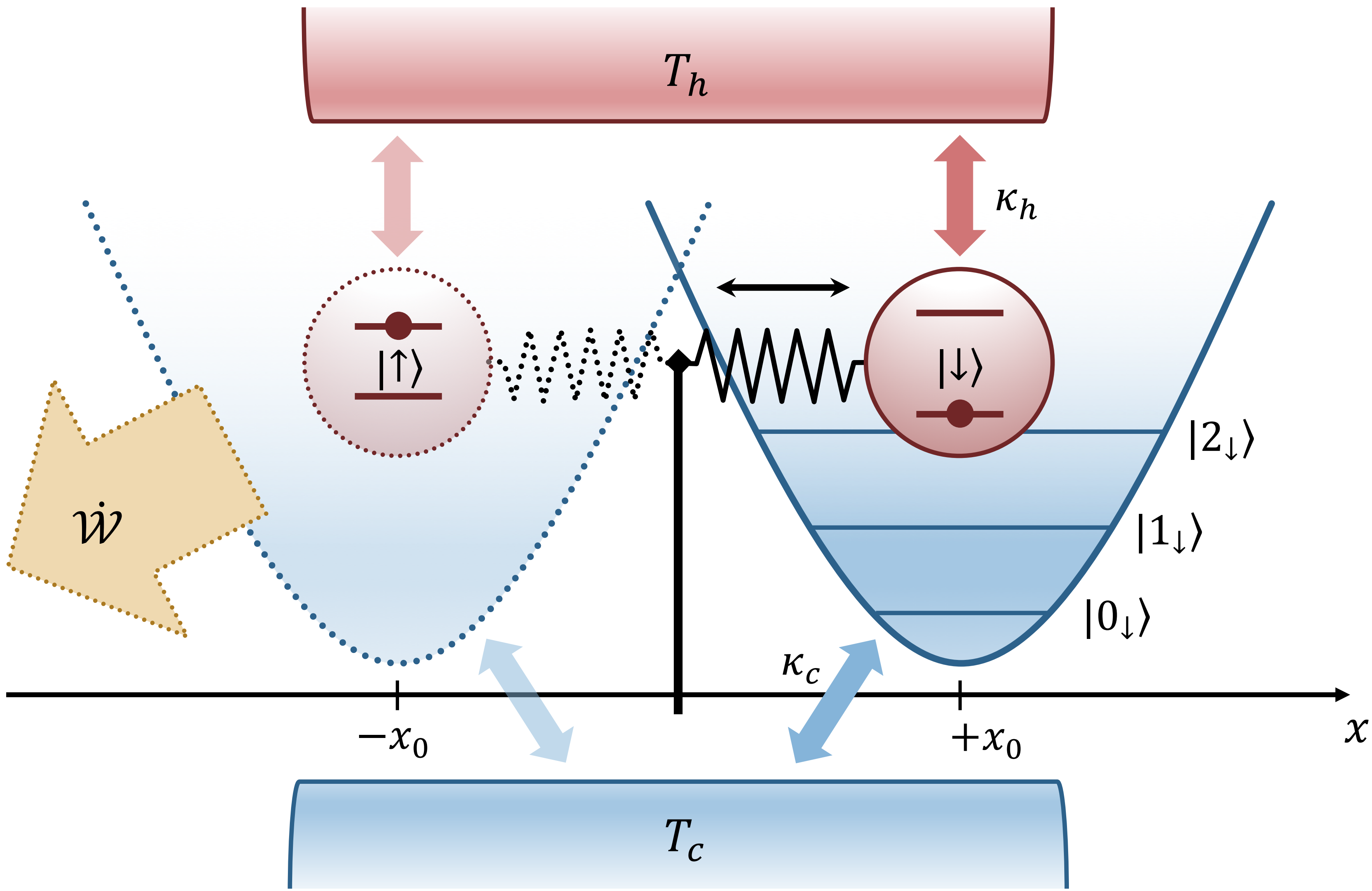
Motivation

- **Self-contained** model
- Thermodynamic **cost of measurement and erasure**
- Origin of **quantum heat**



T_h
κ_h
$|\uparrow\rangle$
$|\downarrow\rangle$
$|2_\downarrow\rangle$
$|1_\downarrow\rangle$
$|0_\downarrow\rangle$
$\dot{\mathcal{W}}$
κ_c
$-x_0$
$+x_0$
x
T_c

Model

- Unitary component:

$$\hat{H} = \frac{\hbar\Omega}{2}\hat{\sigma}_z + \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) + \hbar\omega x_0\hat{\sigma}_z\frac{\hat{a} + \hat{a}^\dagger}{\sqrt{2}}$$

- Measurement cost from work required to shift the pointer:
- **Ideal** pointer = small ω, large x_0

Model

- Unitary component:

$$\hat{H} = \frac{\hbar\Omega}{2}\hat{\sigma}_z + \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) + \hbar\omega x_0\hat{\sigma}_z\frac{\hat{a} + \hat{a}^\dagger}{\sqrt{2}}$$

$$= \frac{\hbar\Omega}{2}\hat{\sigma}_z + \hbar\omega\hat{b}^\dagger\hat{b} + const$$

$$\hat{b} = \hat{a} + \frac{x_0}{\sqrt{2}}\hat{\sigma}_z$$

Model

- Cold bath:

$$\mathcal{L}_c \rho = \kappa_c (\bar{n}_c + 1) \mathcal{D}[\hat{b}]\rho + \kappa_c \bar{n}_c \mathcal{D}[\hat{b}^\dagger]\rho$$

- Hot bath:

$$\mathcal{L}_h \rho = \dots$$

→ For clearly separated states (large x_0)

$$\rho_\infty = (1 - p_\infty)|g\rangle\langle g| \otimes \hat{D}\rho_g \hat{D}^\dagger + p_\infty |e\rangle\langle e| \otimes \hat{D}^\dagger \rho_e \hat{D}$$

1. Direct measure + feedback

- **Continuous incoherent** process at a rate γ
  - Simplest scenario: dichotomic projective measurement given by P (left) and 1-P (right)
  - Conditional spin-flip if we measure left

$$\mathcal{L}_m\rho = \gamma\mathcal{D}[\hat{\sigma}_x\hat{P}]\rho + \gamma\mathcal{D}[\mathbf{1} - \hat{P}]\rho$$

- Steady state deviates more from ρ_∞ for high measurement rates

1. Direct measure + feedback

- **Two** energy terms due to measurement channel:

Work extracted + shift pointer

$$\mathrm{Tr}\left(\hat{H}\mathcal{L}_m\rho\right) = -\gamma\mathrm{Tr}\left(\hat{P}\rho_\infty\hat{P}\left[\hbar\Omega + 2\hbar\omega x_0\hat{x}\right]\hat{\sigma}_z\right\}$$

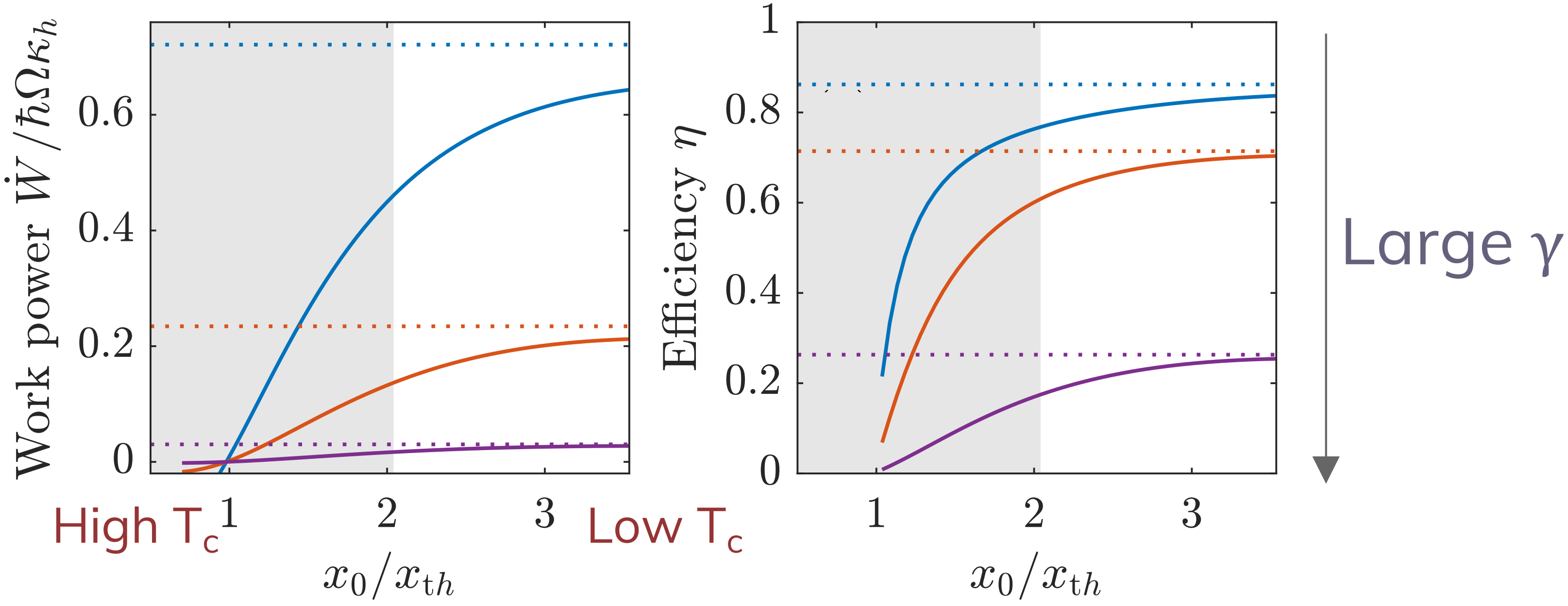
$$+2\gamma\hbar\omega\,\mathrm{Tr}\left(\hat{b}^\dagger\hat{b}\mathcal{D}[\hat{P}]\rho_\infty\right)$$

Backaction noise/dispersion

“Quantum **heat**”

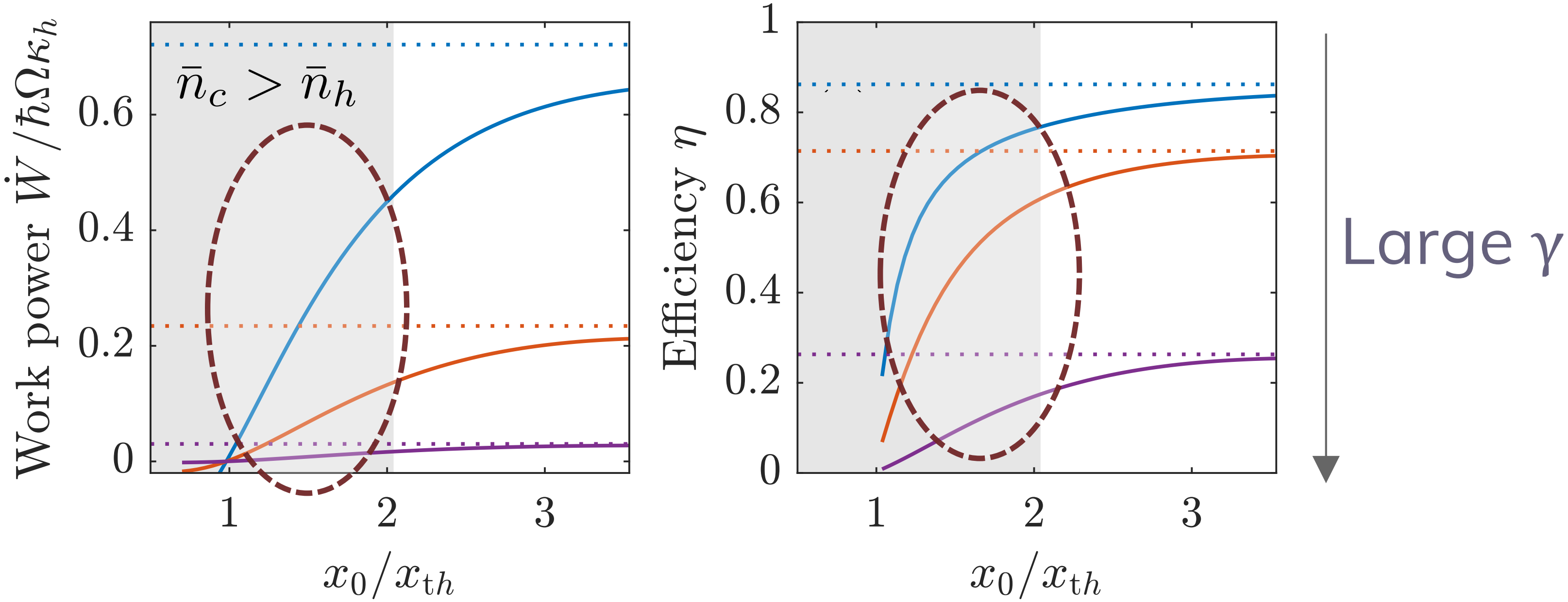
1. Direct measure + feedback

- Ideal efficiency: $\eta_{\text{max}} \approx \dfrac{1 - 2\omega x_0^2/\Omega}{1 + 2[1 + (2\bar{n}_h + 2)\kappa_h/\gamma]\omega x_0^2/\Omega} < \eta_{\text{Otto}}$



1. Direct measure + feedback

- But... **larger operation window** and **no tradeoff** between work and efficiency



2. Non-invasive probing

- Apply position-dependent driving field:

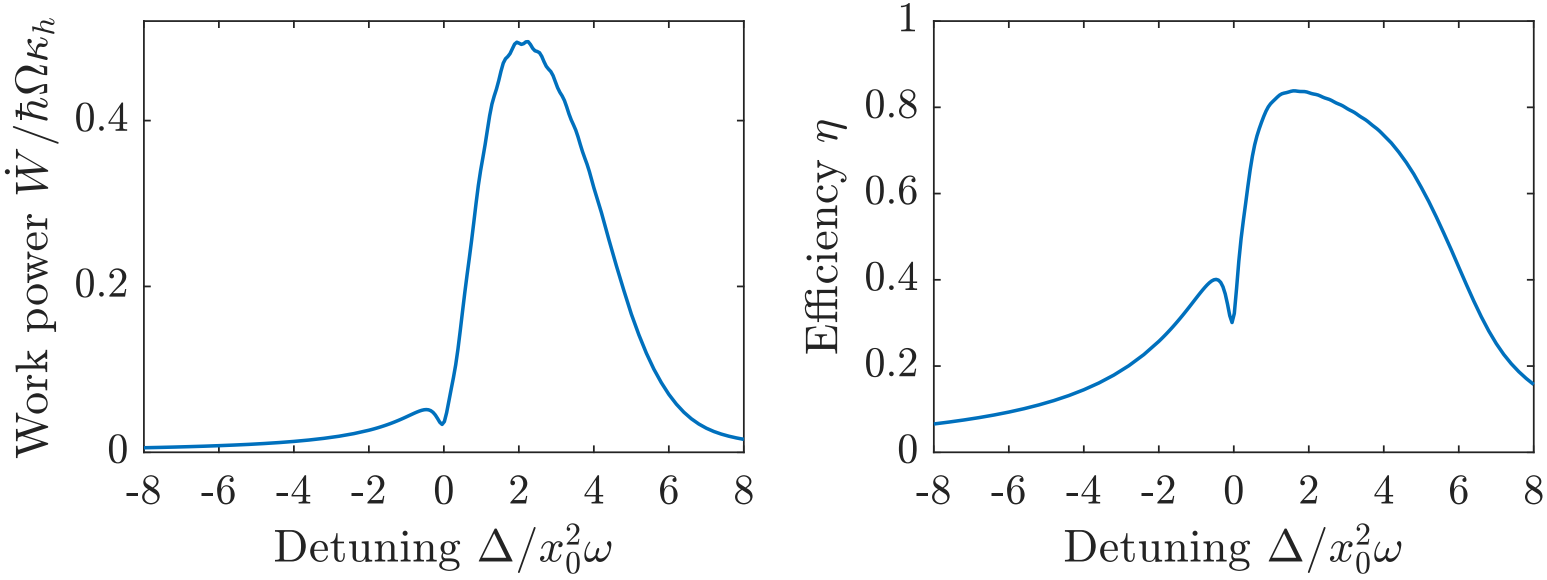
$$\hat{V}(t) = \hbar\zeta f(\hat{x}) e^{-i(\Omega-\Delta)t} |e\rangle\langle g| + h.c.$$

- No ambiguity of work

$$\dot{W} = -\mathrm{Tr}\left\{\rho_\infty(t)\partial_t \hat{V}(t)\right\}$$

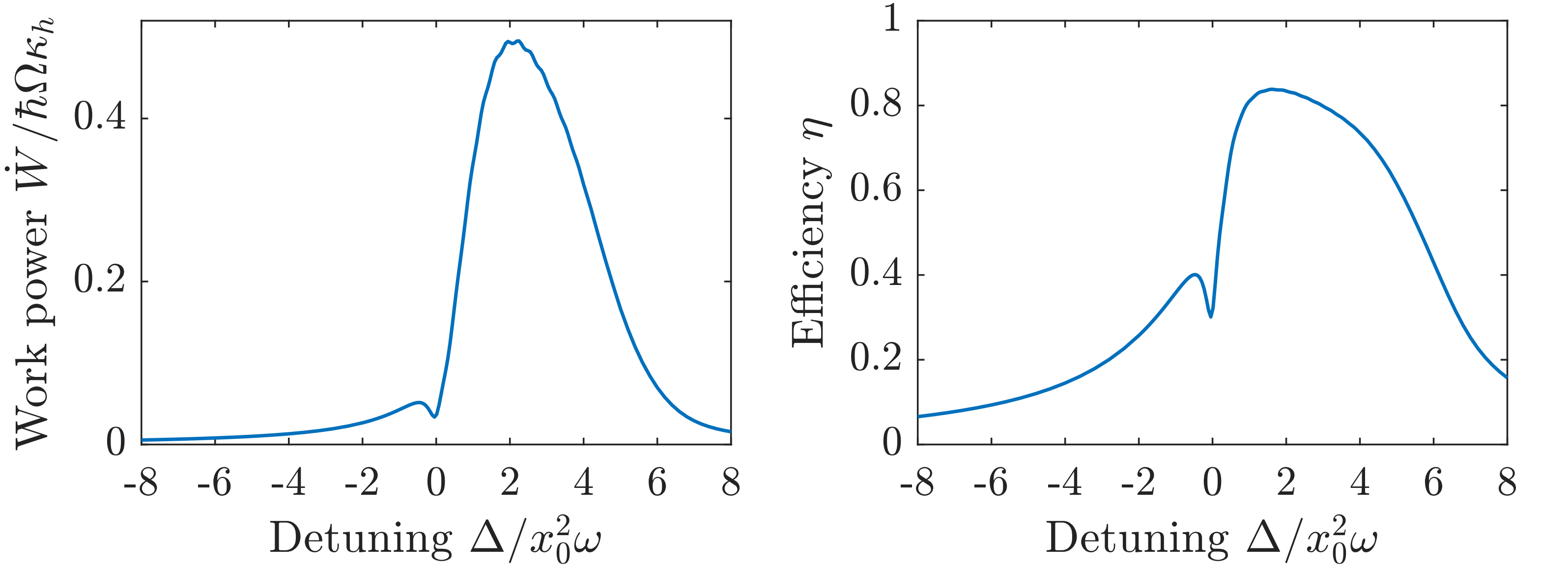
2. Non-invasive probing

- **Poorer** than incoherent measurement
  - Finite feedback time and interaction strength



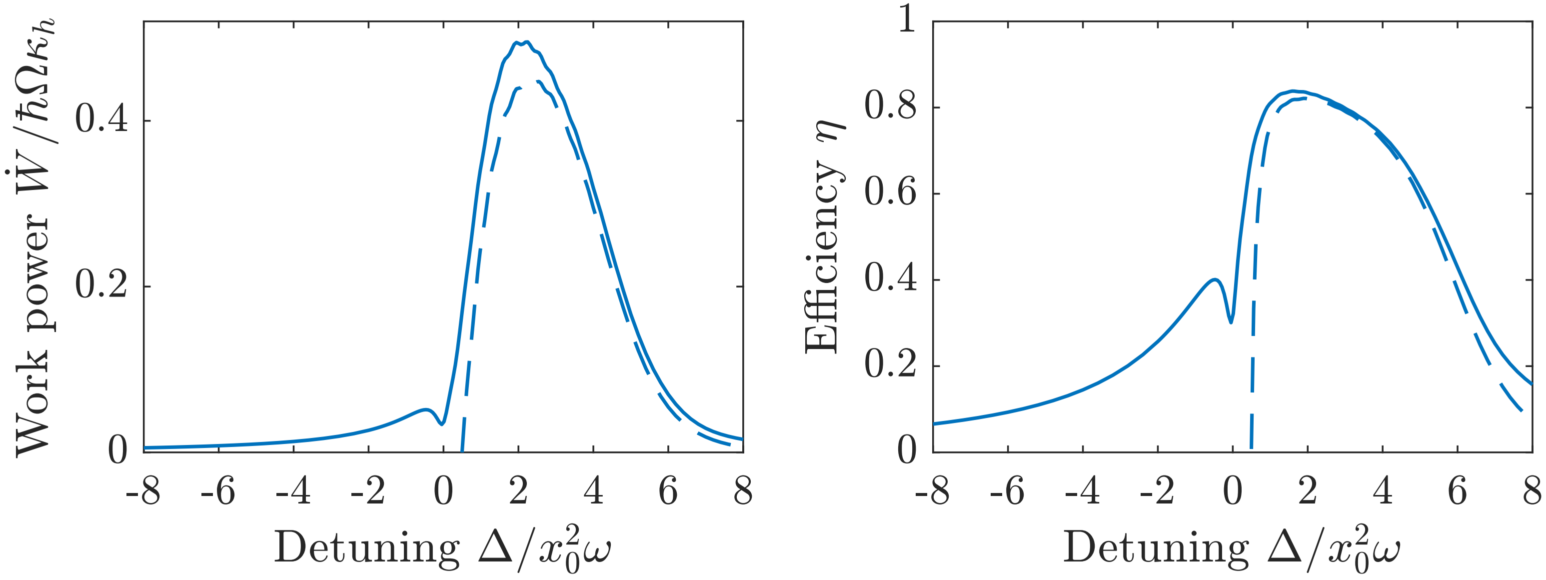
2. Non-invasive probing

- **High power & efficiencies** for $\Delta = 2\omega x_0^2$
  = shift in qubit frequency when pointer is on left



Alternative:

- Probing through **red-detuned** fields that address qubit only when on left **without position dependence**



Conclusions

- (1) incoherent and (2) coherent
    - Also indirect measurement through frequency
- **Simultaneous** high work power and efficiencies
- Bigger operation window than Otto