IAP, June 19, 2017

(Non) equilibrium dynamics: a (broken) symmetry

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Spoiler

Thermal equilibrium dynamics

Symmetry of action

$$\psi \mapsto \mathcal{T}_\beta[\psi]$$

$$S[\psi] = \int \mathrm{d}x \, \mathcal{L}(\psi(x), \partial_\mu \psi(x); x) \mapsto S[\psi]$$

Ward-Takahashi identies

$$\langle \mathcal{O}[\psi(x)] \ldots \mathcal{O}[\psi(x')] \rangle = \langle \mathcal{O}[\mathcal{T}_\beta \psi(x)] \ldots \mathcal{O}[\mathcal{T}_\beta \psi(x')] \rangle$$

Spoiler

Non-equilibrium

~~Thermal equilibrium~~ dynamics

↕

~~Symmetry~~ of action

Symmetry breaking

$$\psi \mapsto \mathcal{T}_\beta[\psi]$$

$$S[\psi] = \int \mathrm{d}x\, \mathcal{L}(\psi(x), \partial_\mu \psi(x); x) \mapsto S[\psi] + \Delta S[\psi]$$

Entropy production

Fluctuation theorems

~~Ward-Takahashi identies~~

$$\langle \mathcal{O}[\psi(x)] \ldots \mathcal{O}[\psi(x')] \rangle = \langle \mathcal{O}[\mathcal{T}_\beta \psi(x)] \ldots \mathcal{O}[\mathcal{T}_\beta \psi(x')]\, \mathrm{e}^{\Delta S} \rangle$$

Spoiler

Non-equilibrium 2

1 ~~Thermal equilibrium~~ dynamics

↕ 6

5

~~Symmetry~~ of action

Symmetry breaking

7

$$\psi \mapsto \mathcal{T}_\beta[\psi]$$

$$S[\psi] = \int \mathrm{d}x\, \mathcal{L}(\psi(x), \partial_\mu \psi(x); x) \mapsto S[\psi] + \Delta S[\psi]$$

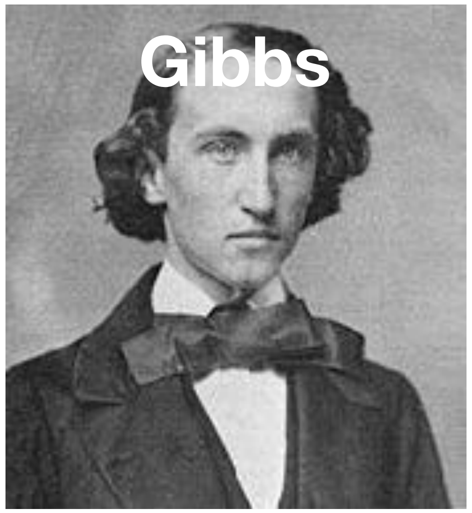
4 Fluctuation theorems

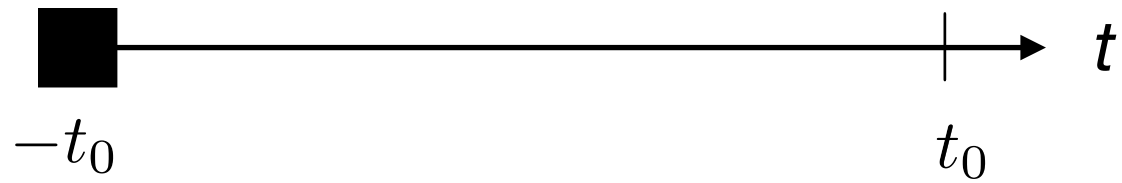
3 Entropy production

~~Ward-Takahashi identies~~

$$\langle \mathcal{O}[\psi(x)] \ldots \mathcal{O}[\psi(x')] \rangle = \langle \mathcal{O}[\mathcal{T}_\beta \psi(x)] \ldots \mathcal{O}[\mathcal{T}_\beta \psi(x')]\, \mathrm{e}^{\Delta S} \rangle$$

Equilibrium dynamics





	preparation	evolution
Classical	$P_{\rm GB}(x,\dot{x}) \sim \mathrm{e}^{-\beta\mathcal{E}(x,\dot{x})}$	$m\ddot{x} = -V'(x)$
Quantum	$\hat{\rho}_{\rm GB} \sim \mathrm{e}^{-\beta\hat{H}}$	$\hat{O}_{\rm H}(t) = \mathrm{e}^{\mathrm{i}\hat{H}t}\,\hat{O}\,\mathrm{e}^{-\mathrm{i}\hat{H}t}$

Equilibrium conditions
- prepare in equilibrium at temperature β^{-1} wrt $\hat{H}$
- evolve with same $\hat{H}$
- (coupled to bath at β^{-1})

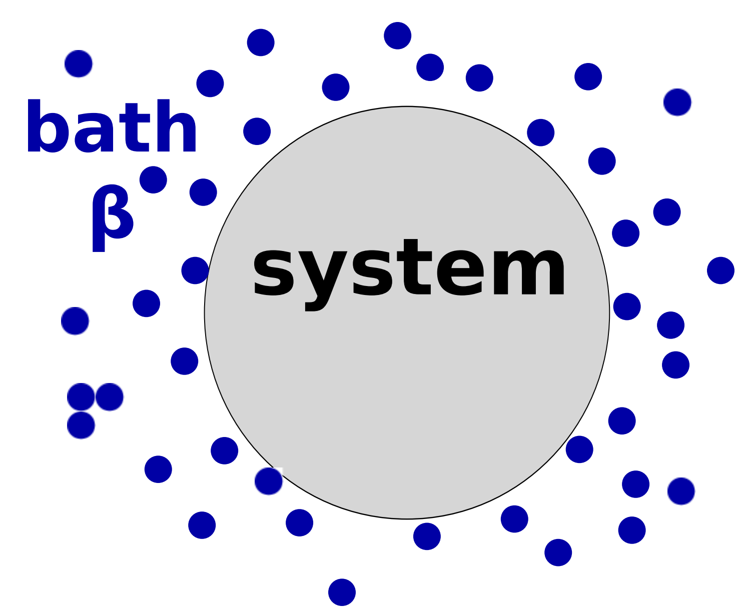
Prepare

- With thermostat

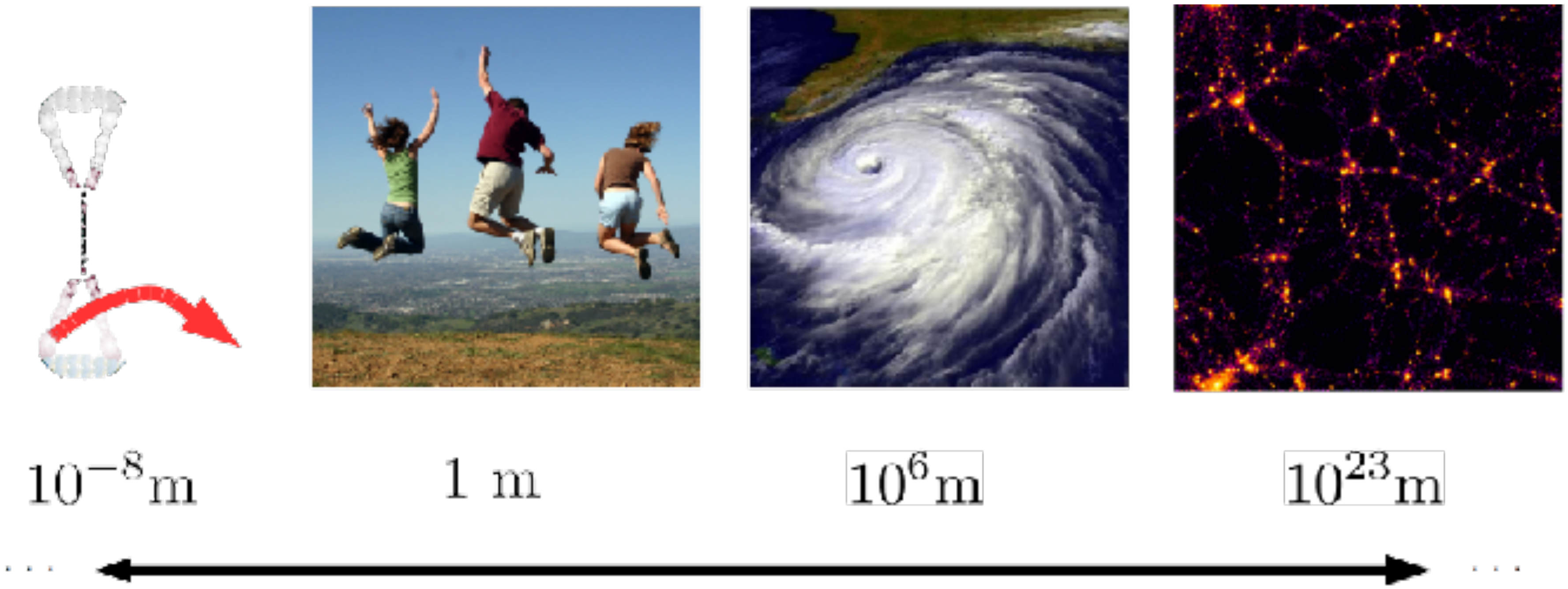
$$\text{ex: } m\ddot{x} = -V'(x) - \eta\dot{x} + \xi(t)$$

$$\langle \xi(t)\xi(t')\rangle = 2\eta\beta^{-1}\,\delta(t-t')$$

- Isolated (thermalization)



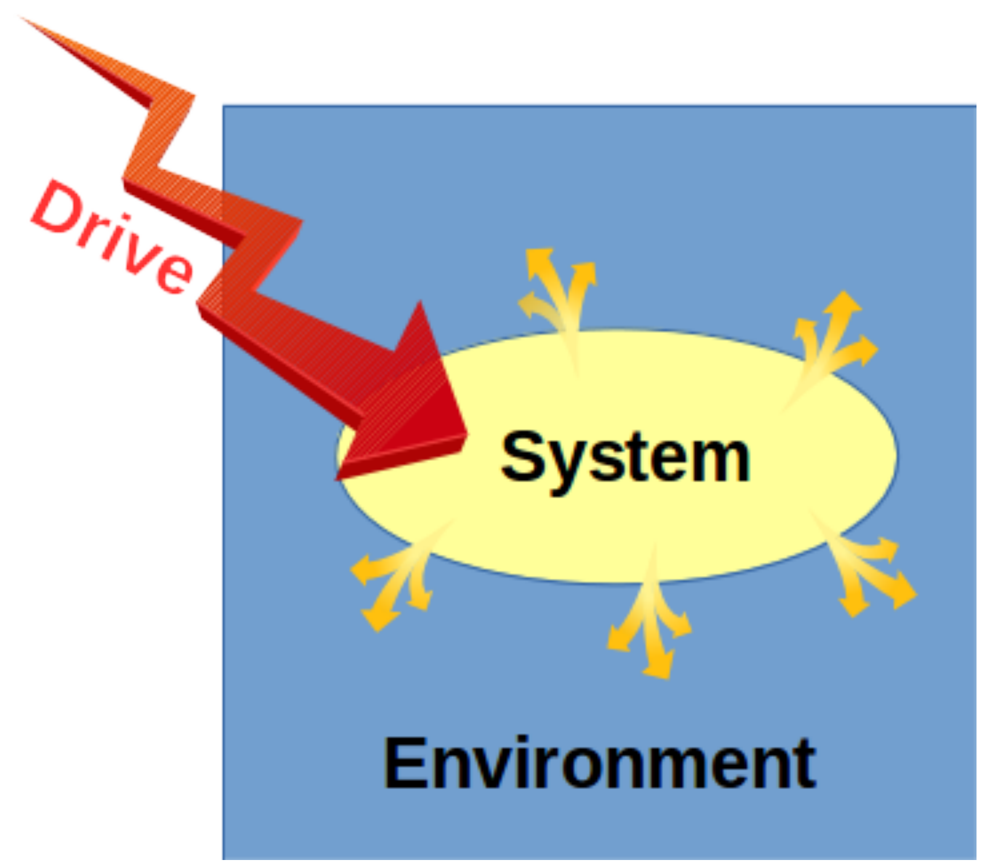
Non-equilibrium dynamics



- relaxation dynamics: quench $\hat{H}_0 \mapsto \hat{H}$

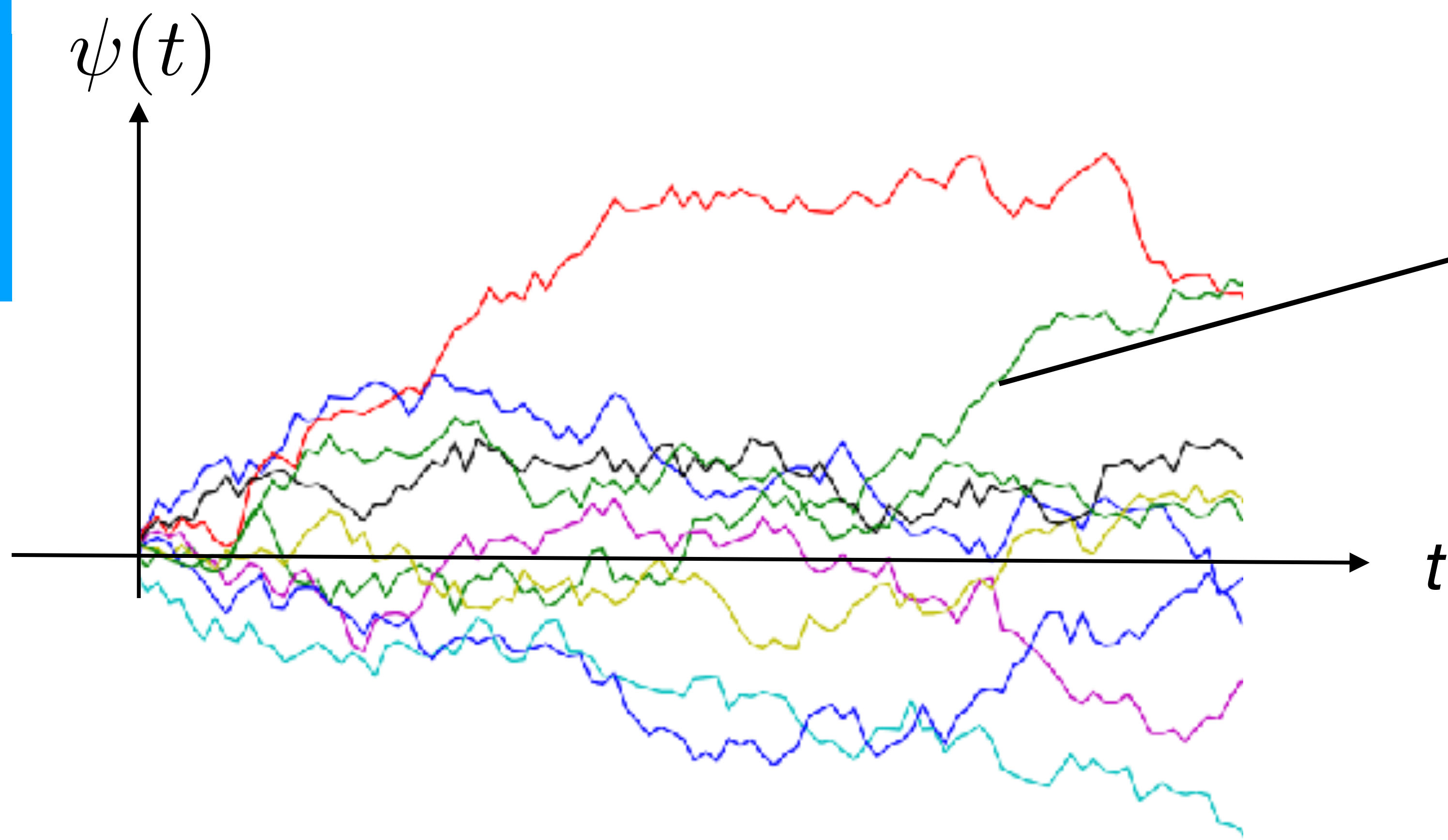
- non-equilibrium drive:
  - time-dependent $\hat{H}(t)$ (work)
  - environment (currents)

- non-equilibrium “engineering”



Stochastic thermodynamics

classical



single trajectory

- work $\mathcal{W}[\psi]$
- heat $\mathcal{Q}[\psi]$
- entropy $\mathcal{S}[\psi]$

First law

$$\Delta\mathcal{E} = \mathcal{W}[\psi] + \mathcal{Q}[\psi]$$

Second law

$$\Delta S = \beta\mathcal{Q}[\psi] + \underbrace{\mathcal{S}^{\rm irr}[\psi]}$$

in average $\langle\mathcal{S}^{\rm irr}[\psi]\rangle \geq 0$

Fluctuation Theorem

$$P(\mathcal{S}^{\rm irr}) = P_{\rm r}(-\mathcal{S}^{\rm irr})\,\mathrm{e}^{\mathcal{S}^{\rm irr}}$$

Gallavoti Cohen (1995)

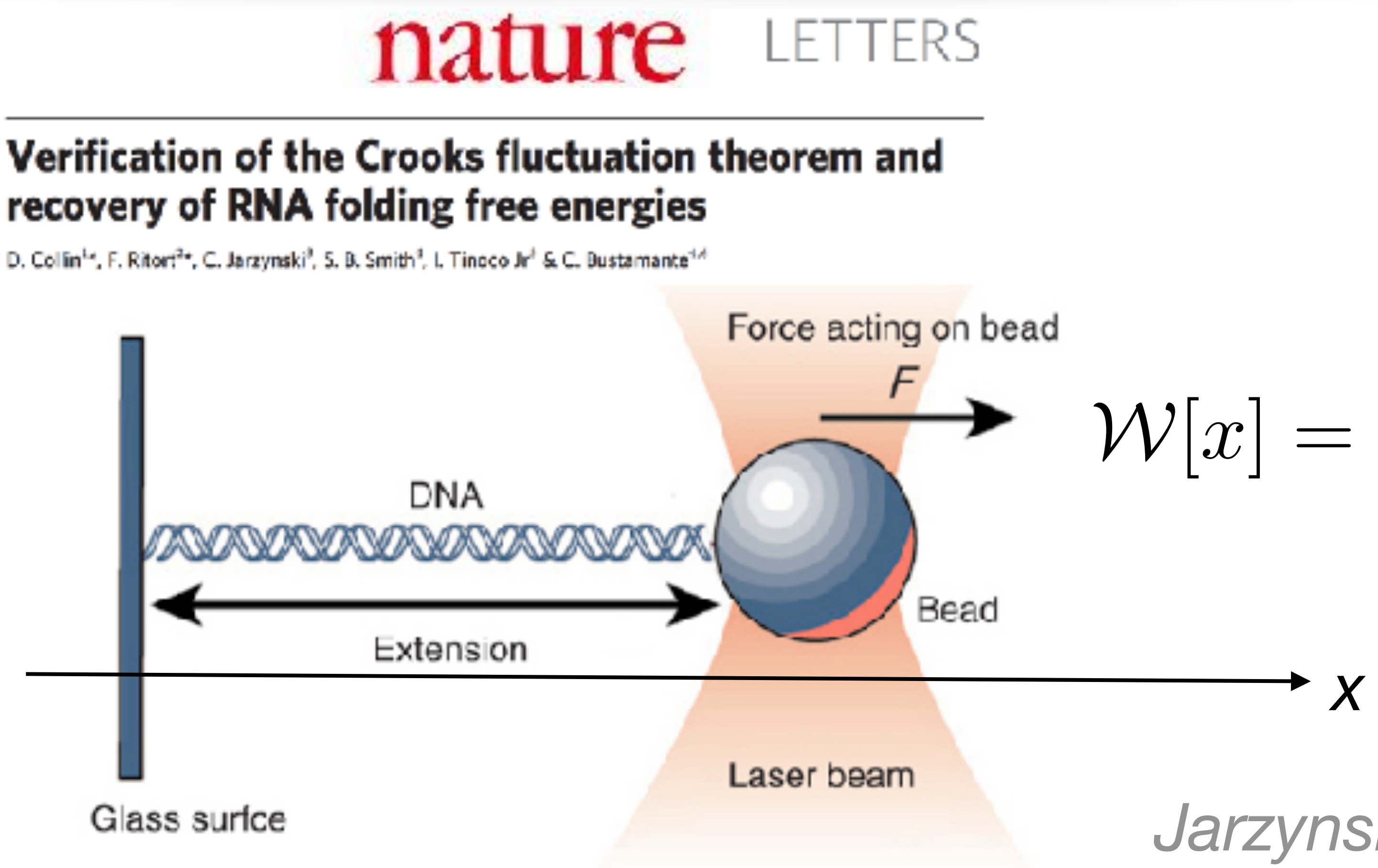
Fluctuation theorems

classical

Work fluctuation theorem

$$P(\mathcal{W}) = P_{\mathrm{r}}(-\mathcal{W})\, \mathrm{e}^{\beta(\mathcal{W}-\Delta\mathcal{F})}$$

Crooks (1999)



$$\mathcal{W}[x] = \sum_i F_i\, \Delta x_i$$

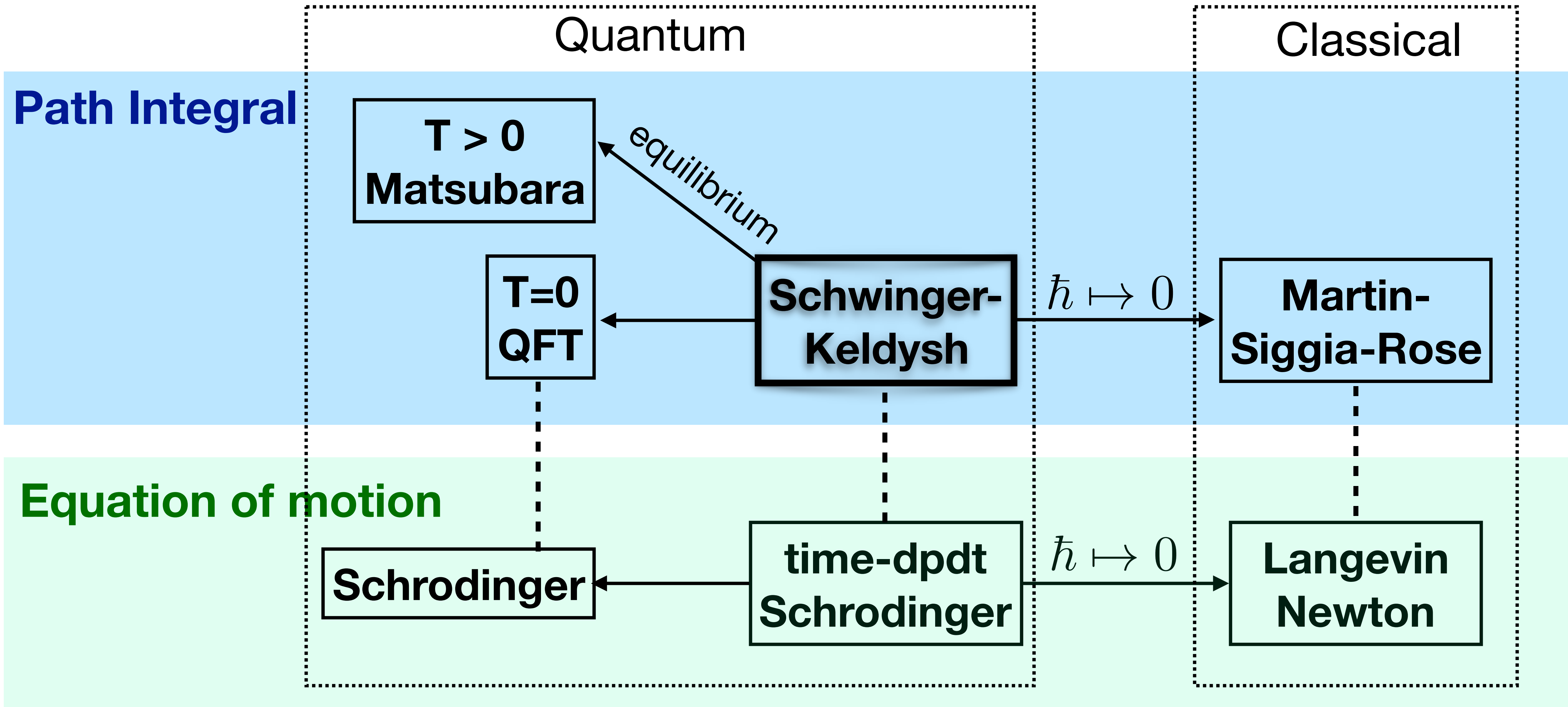
Jarzynski et al. (2005)

Quantum trajectories

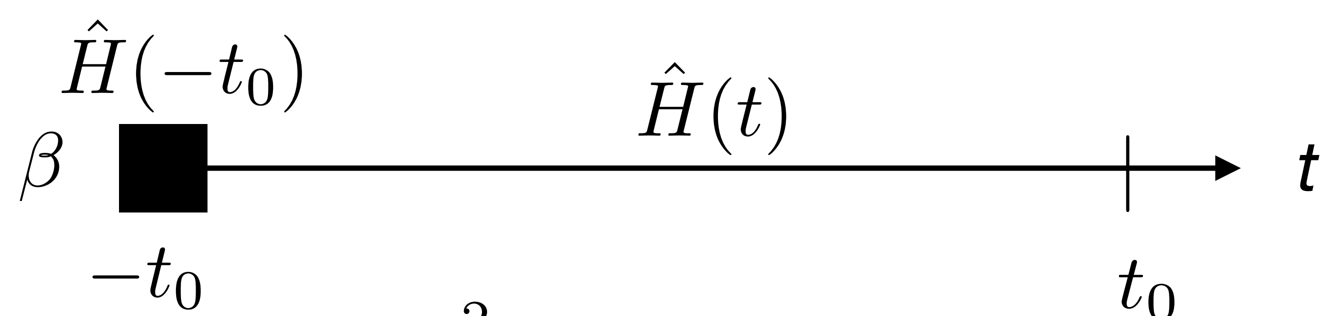
quantum

- ☑ Work fluctuation theorem *(Kurchan 2000)*
- ☐ Entropy production ?
- ☐ Entropy fluctuation theorem ?

Formalisms

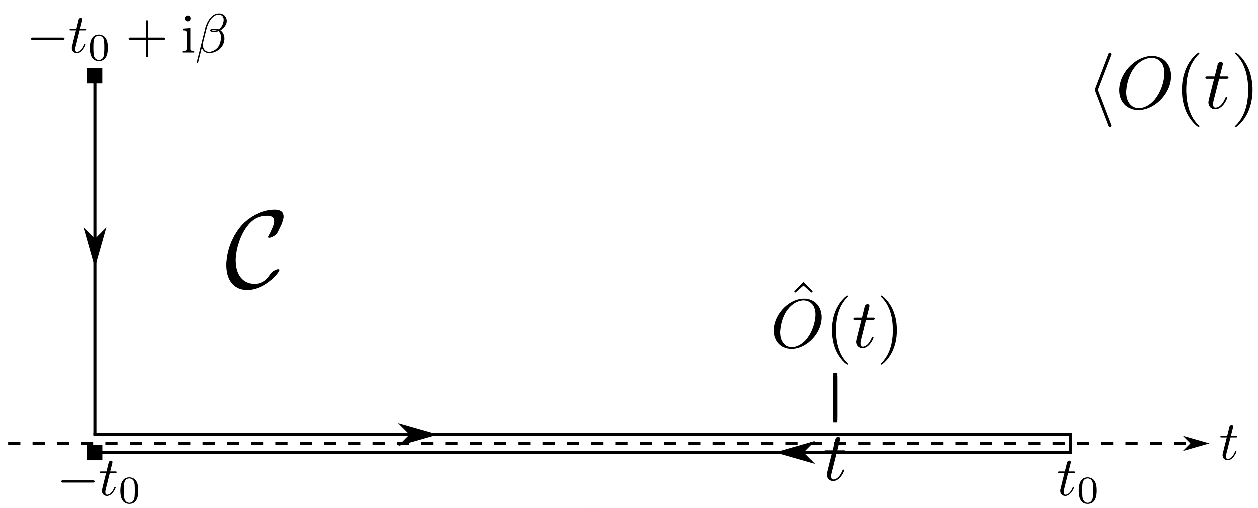


non-relativistic real scalar field $\psi(t)$



$$\text{ex:}\ \ \hat{H}(t) = \frac{\pi^2}{2m} + V(\psi; t)$$

Schwinger-Keldysh formalism



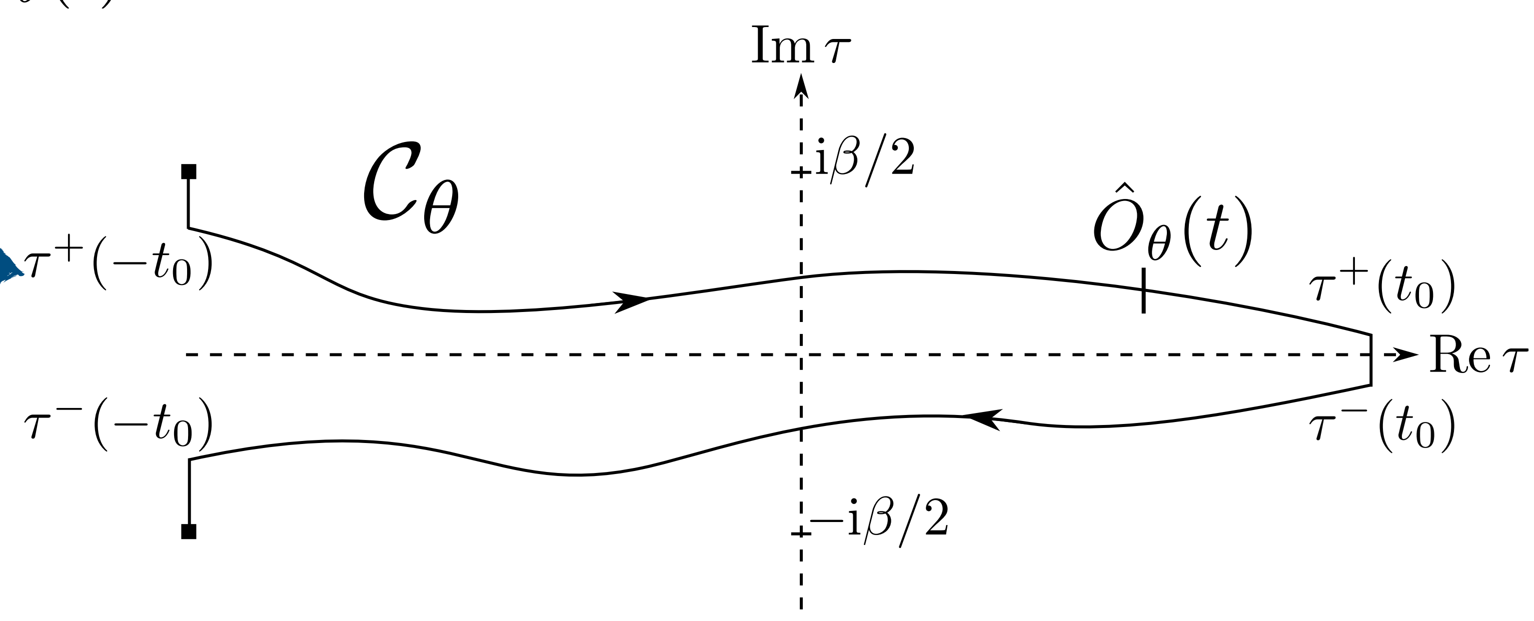
$$\begin{aligned}
\langle O(t)\rangle &= \mathcal{Z}^{-1}\,\mathrm{Tr}\left[\mathrm{e}^{\mathrm{i}\hat{H}t}\,\hat{O}(t)\,\mathrm{e}^{-\mathrm{i}\hat{H}t}\,\mathrm{e}^{-\beta\hat{H}}\right] \\
&= \mathcal{Z}^{-1}\,\mathrm{Tr}\left[\mathrm{T}_{\mathcal{C}}\,\mathrm{e}^{\mathrm{i}\int_{\mathcal{C}}\mathrm{d}\tau\;\hat{H}}\,\hat{O}(t)\right] \\
&= \mathcal{Z}^{-1}\int\mathcal{D}[\psi]\,\mathrm{e}^{\mathrm{i}\int_{\mathcal{C}}\mathrm{d}\tau\;\mathcal{L}[\psi(\tau)]}\,\langle\psi(t)|\hat{O}(t)|\psi(t)\rangle
\end{aligned}$$

Novel formal degree of freedom

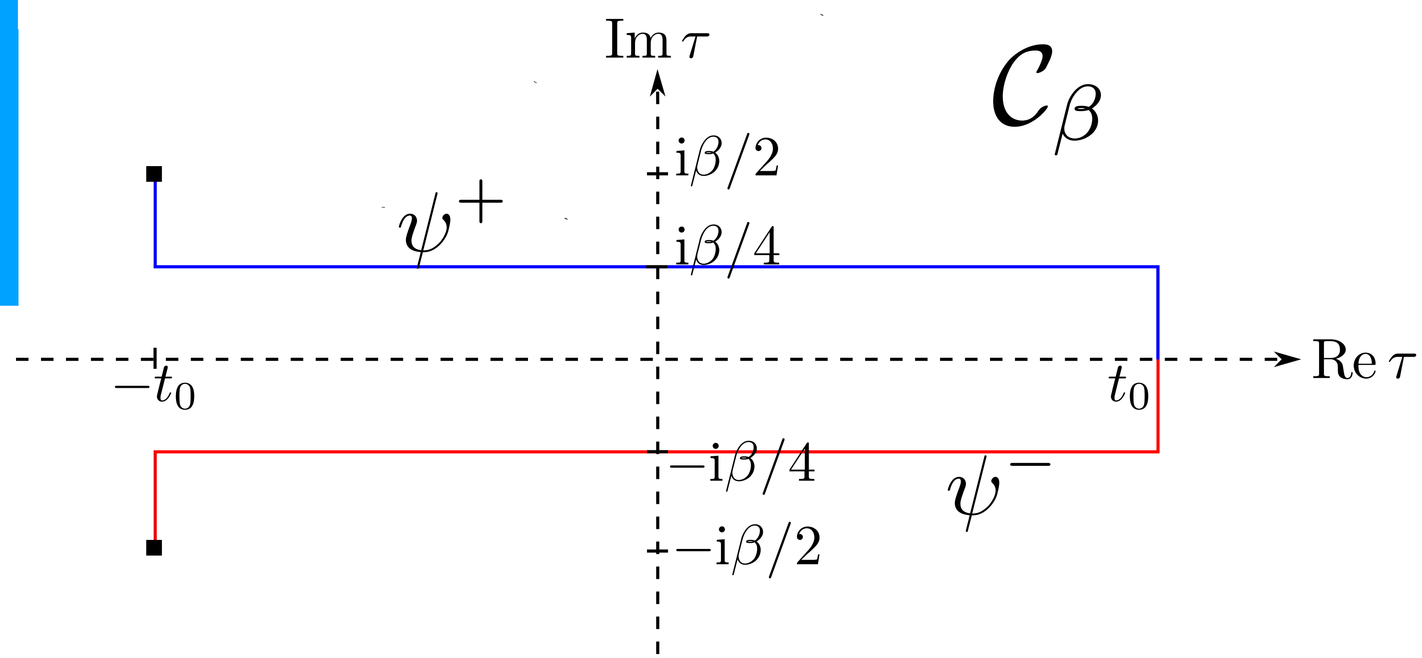
$$t \mapsto \tau = t + \theta(t) \qquad\qquad \psi(t) \mapsto \psi(\tau)$$

$$\mathbb{I} = \int \mathrm{d}\psi(t)\;\;\mathrm{e}^{+\mathrm{i}\theta(t)\hat{H}}\,|\psi(t)\rangle\langle\psi(t)|\mathrm{e}^{-\mathrm{i}\theta(t)\hat{H}}$$

$$\hat{O} \mapsto \hat{O}_\theta(t) \equiv \mathrm{e}^{-\mathrm{i}\theta(t)\hat{H}}\,\hat{O}\,\mathrm{e}^{\mathrm{i}\theta(t)\hat{H}}$$



Symmetry of equilibrium



$$\hat{H} = \text{const.}$$

$$S[\psi] = \int_{\mathcal{C}_\beta} \mathrm{d}\tau \, \mathcal{L}[\psi(\tau)]$$

Field transformation

$$\mathcal{T}_\beta : \; \psi^\pm(\tau) \mapsto \psi^\pm(-\tau \pm \mathrm{i}\beta/2)$$

$$\mathcal{T}_\beta \circ \mathcal{T}_\beta = \mathrm{Id}$$

Invariance of the action

$$\beta\mathcal{F}(-t_0) + \mathrm{i}S[\psi] \overset{\mathcal{T}_\beta}{\mapsto} \beta\mathcal{F}(-t_0) + \mathrm{i}S[\psi]$$

Consequences of the symmetry

Ward-Takahashi identies

$$\langle \psi^a(\tau)\,\psi^b(\tau')\,\ldots\rangle_{\mathcal{S}_\beta} = \langle \mathcal{T}_\beta\psi^a(\tau)\,\mathcal{T}_\beta\psi^b(\tau')\,\ldots\rangle_{\mathcal{S}_\beta}$$

Keldysh Green's functions

$$\mathrm{i}G^{ab}(t,t') = \langle \psi^a(t)\,\psi^b(t')\rangle \quad a,b=+,-$$

Fluctuation-dissipation theorem

$$G^{-+}(t,t') \stackrel{\mathcal{T}_\beta}{=} \mathrm{e}^{\mathrm{i}\beta/2\,(\partial_t-\partial_{t'})}\, G^{+-}(-t',-t)$$

Classical limit

$$\left.\frac{\delta\langle\psi(t)\rangle}{\delta f(t')}\right|_{f=0} = -\beta\,\partial_t\,\langle\psi(t)\psi(t')\rangle \quad \text{if } t>t'$$

$$= 0 \qquad\qquad \text{if } t<t'$$

Symmetry breaking

Time-dependent drive: $\hat{H} \mapsto \hat{H}(t)$

$$S[\psi] = \int_{\mathcal{C}_\beta} \mathrm{d}\tau \; \mathcal{L}[\psi(\tau); t(\tau)] + \int_{\mathcal{C}_\beta} \mathrm{d}t \; \widetilde{\mathcal{L}}[\psi(\tau)); t(\tau)]$$

New !

Variation of the action

$$\beta\mathcal{F}(-t_0) + \mathrm{i}S[\psi] \overset{\mathcal{T}_\beta}{\mapsto} \beta\mathcal{F}_\mathrm{r}(-t_0) + \mathrm{i}S_\mathrm{r}[\psi] + \beta\Delta\mathcal{F}_\mathrm{r} - \Sigma_\mathrm{r}[\psi]$$

New !

$\mathcal{S}_\mathrm{r}^\mathrm{irr}[\psi]$

with

$$\Sigma[\psi] = \int_{\mathcal{C}} \mathrm{d}t \; \langle\psi(t)| \, \mathrm{e}^{\beta/4\,\hat{H}(t)} \left[\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{e}^{-\beta/2\,\hat{H}(t)}\right] \mathrm{e}^{\beta/4\,\hat{H}(t)} \, |\psi(t)\rangle$$

$\xrightarrow{\hbar \mapsto 0} \beta\mathcal{W}[\psi]$

Symmetry breaking

Measure of irreversibility

$$\mathcal{S}^{\rm irr}[\psi] = \beta\Delta\mathcal{F} - \Sigma[\psi]$$

$$\Sigma[\psi] = \int_{\mathcal{C}} \mathrm{d}t \, \langle\psi(t)| \mathrm{e}^{\beta/4\,\hat{H}(t)} \left[\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{e}^{-\beta/2\,\hat{H}(t)}\right] \mathrm{e}^{\beta/4\,\hat{H}(t)} |\psi(t)\rangle$$

- ☑ $\langle \mathcal{S}^{\rm irr}[\psi]\rangle \geq 0$
- ☑ Classical limit
- ☑ Reversible process

☑ Fluctuation Theorem

$$P(\mathcal{S}^{\rm irr}) = P_{\rm r}(-\mathcal{S}^{\rm irr})\,\mathrm{e}^{\mathcal{S}^{\rm irr}}$$

Entropy production operator ?

Recap

Non-equilibrium

~~Thermal equilibrium~~ dynamics

↕

~~Symmetry~~ of action

Symmetry breaking

$$S[\psi] \overset{\mathcal{T}_\beta}{\longmapsto} S[\psi] + \mathcal{S}^{\mathrm{irr}}[\psi]$$

Entropy production

Fluctuation theorems

~~Ward-Takahashi identies~~

$$\langle \mathcal{O}[\psi(\tau)] \dots \mathcal{O}[\psi(\tau')] \rangle = \langle \mathcal{O}[\mathcal{T}_\beta \psi(\tau)] \dots \mathcal{O}[\mathcal{T}_\beta \psi(\tau')]\, \mathrm{e}^{\mathcal{S}_{\mathrm{r}}^{\mathrm{irr}}[\psi]} \rangle_{\mathrm{r}}$$