Resource theories of nonclassicality and thermodynamics in bosonic quantum systems

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Imperial College London
NANYANG TECHNOLOGICAL UNIVERSITY
CQT Centre for Quantum Technologies
Australian National University

What is a resource theory?

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Operational limitations

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Operational limitations ⟷ Resource states / operations

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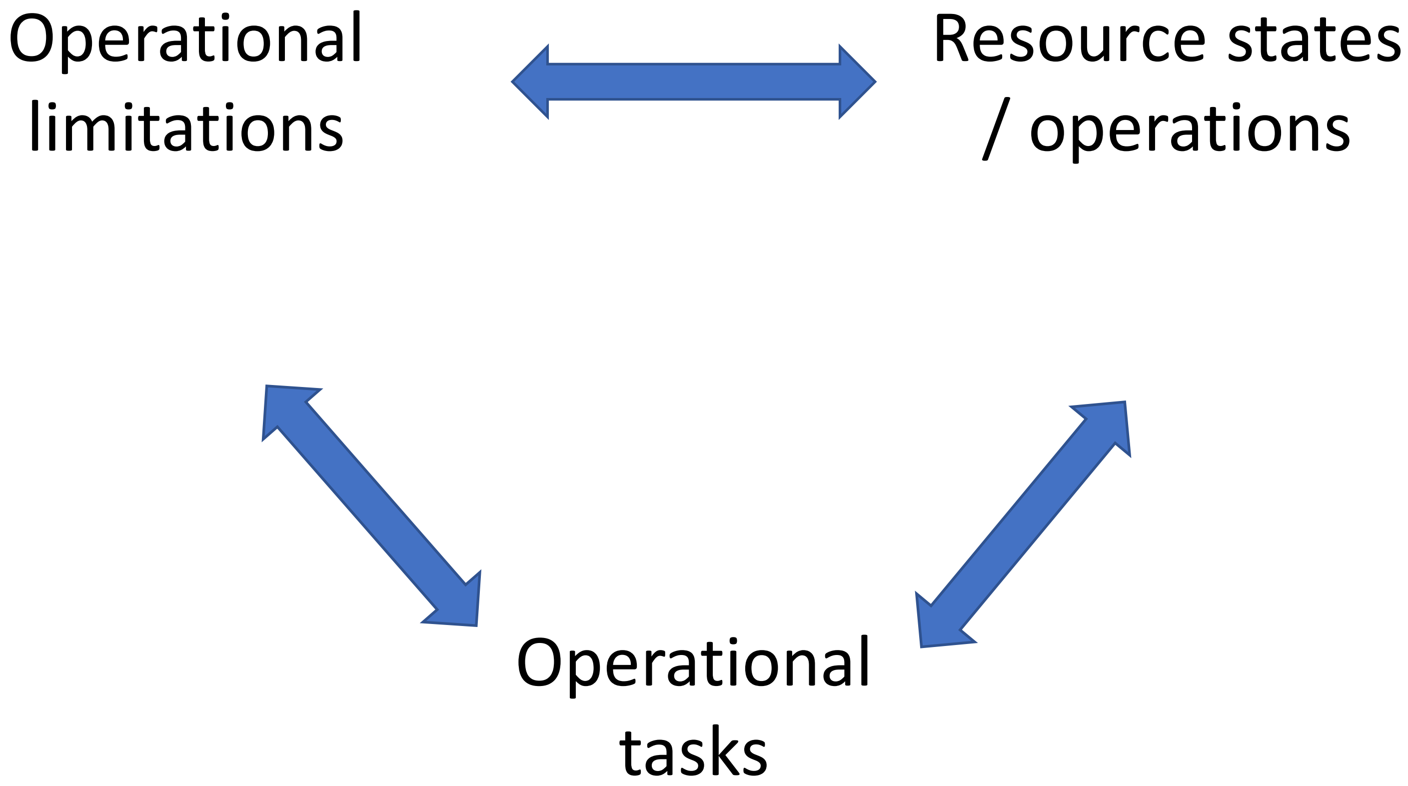

What is a resource theory?

Operational limitations

Compass–straightedge constructions
Local operations (and variants)
Thermalizing channels

Resource states / operations

Quadratrix
Entanglement; quantum channels
Non-equilibrium states

Operational tasks

Squaring circles; trisecting angles
Teleportation; superdense coding
Work extraction; refrigeration; erasure

Resource theories for continuous-variable systems

Resources: Non-Gaussianity ● Non-classicality ● Entanglement ● Thermal non-equilibrium

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- Classicality is relative to overcomplete, non-orthogonal basis
- Difficult to understand entanglement beyond Gaussian states
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Recent work (2017–18):

- Tan *et al.*, **Quantifying the Coherence between Coherent States**. PRL 119, 190405
- Theurer *et al.*, **Resource Theory of Superposition**. PRL 119, 230401
- Lami *et al.*, **Gaussian quantum resource theories**. arXiv:1801.05450
- Zhuang *et al.*, **Resource theory of non-Gaussian operations**. PRA 97, 052317
- Takagi and Zhuang, **Convex resource theory of non-Gaussianity**. PRA 97, 062337
- Kwon *et al.*, **Nonclassicality of Light as a Quantifiable Resource for Quantum Metrology**. arXiv:1804.09355
- Albarelli *et al.*, **Resource theory of quantum non-Gaussianity and Wigner negativity**. PRA 98, 052350 (Alessandro Ferraro's talk at QIPA 2018)

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- But $|\alpha\rangle$ basis is **non-orthogonal**, **overcomplete**!

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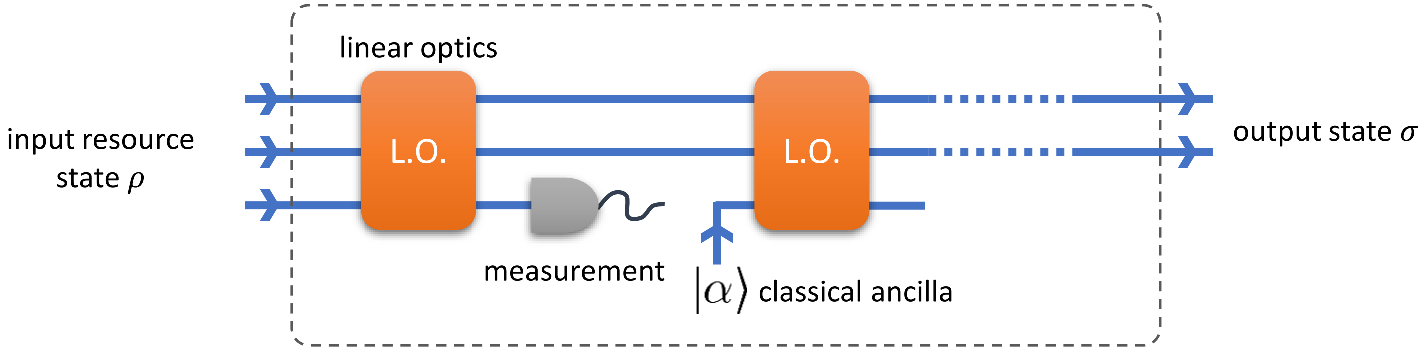

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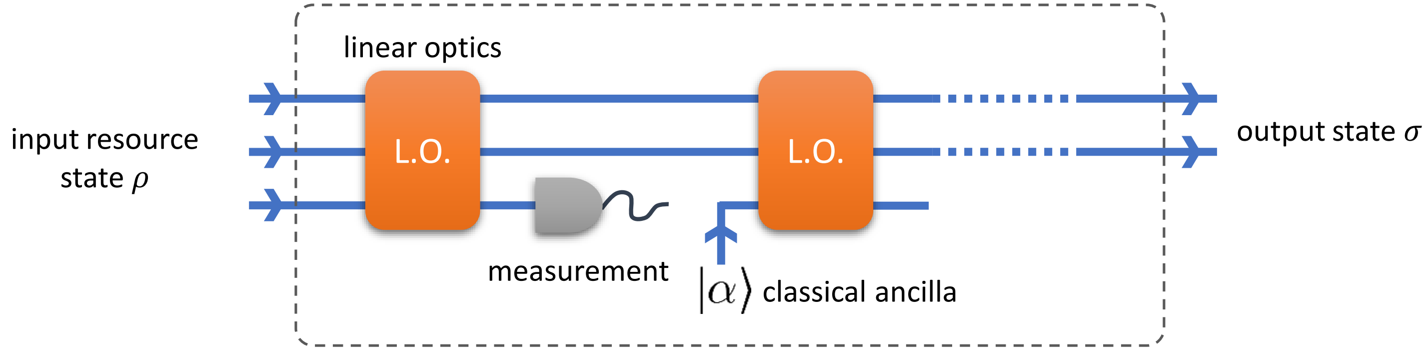

Can consider different numbers of measurement rounds
For n measurement rounds, the class of operations is denoted $\mathcal{P}_n$

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- Well-known measures of nonclassicality fail to reflect this!
  [Hillery, PRA 35, 725 (1987); Lee, PRA 44, R2775 (1991)]

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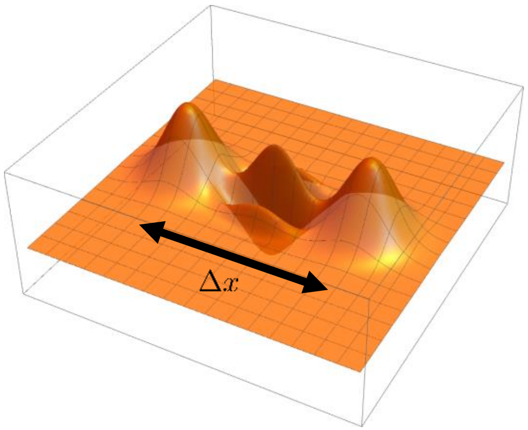

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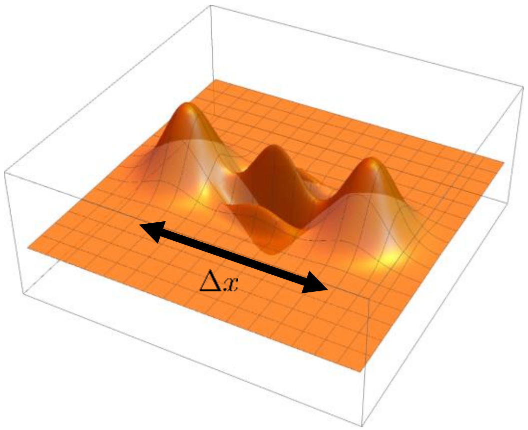

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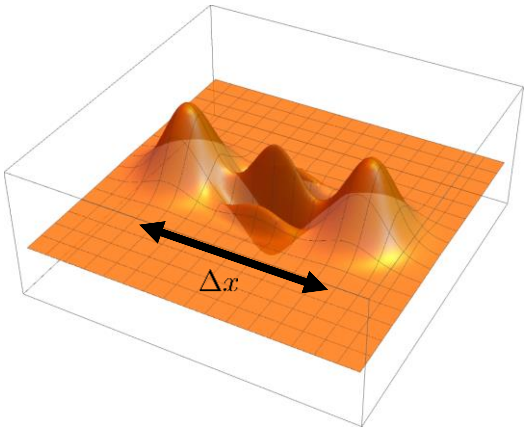

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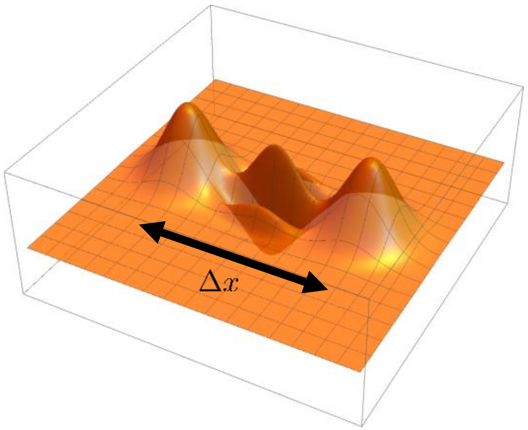

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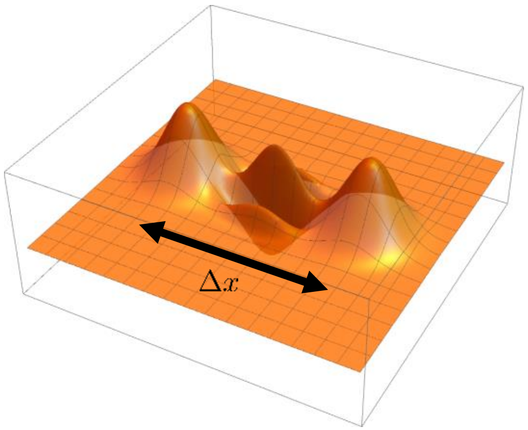

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E.g. there is a protocol for "growing" cat states: $(|\alpha\rangle + |-\alpha\rangle)^{\otimes 2} \mapsto |\sqrt{2}\alpha\rangle + |-\sqrt{2}\alpha\rangle$

Applying this result: success probability $\leq \frac{1}{2}$

Lund et al., PRA 70, 020101 (2004)

Phase-space variance for mixed states

- Extension to mixed states: Convex roof of pure-state measure

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  - Crucially, also a monotone under $\mathcal{P}_n$

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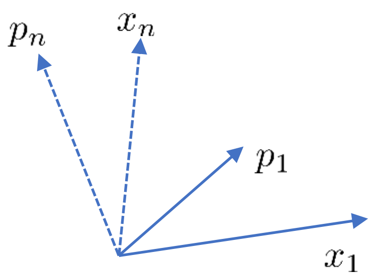

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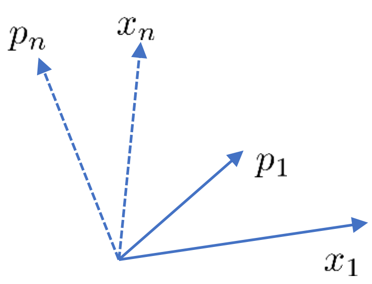

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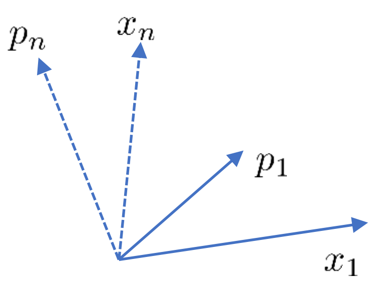

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Under $\mathcal{P}_0$ (i.e., without measurements), this concentration of utility for parameter estimation is impossible.

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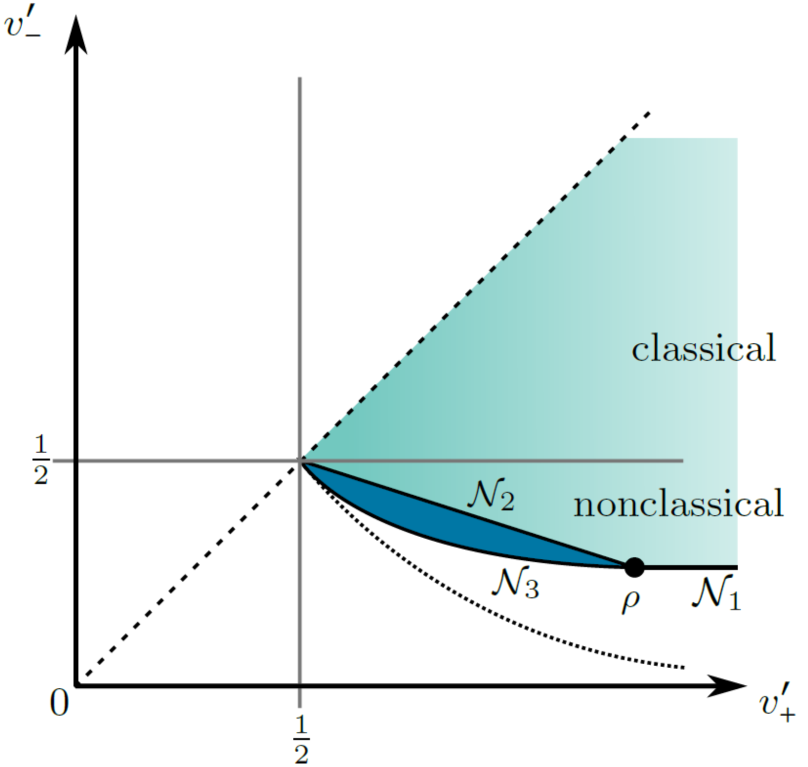
- Completely characterised by covariance matrix
- 1-mode case: is ρ more nonclassical than σ if it is more squeezed?
- Surprisingly, reduction in squeezing is necessary for a $\mathcal{P}_n$ transformation but not sufficient!

  A second constraint is needed:

There is a trade-off between removing noise and maintaining squeezing



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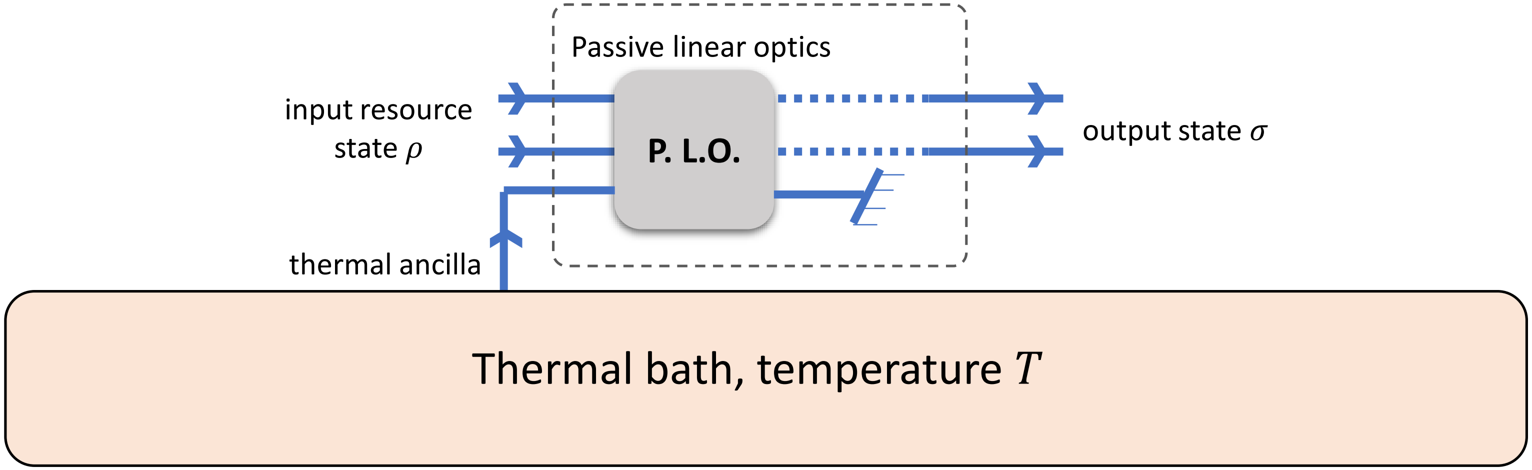
Gaussian thermal operations (GTO)



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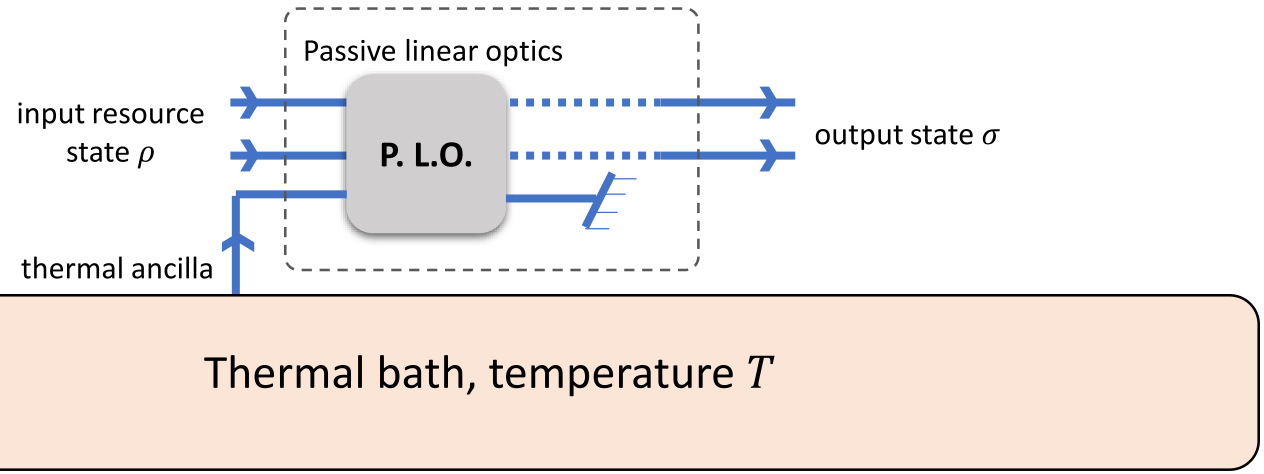

- Adaptation of finite-dimensional thermal operations framework*
- Passive linear optics: built-in First Law of Thermodynamics
- Gaussian dilations, but all ancillary states thermal at T
- More restrictive than operations in nonclassicality resource theory

*Brandão *et al.*, **Resource Theory of Quantum States Out of Thermal Equilibrium**.
PRL 111, 250404.

Laws of Gaussian thermodynamics

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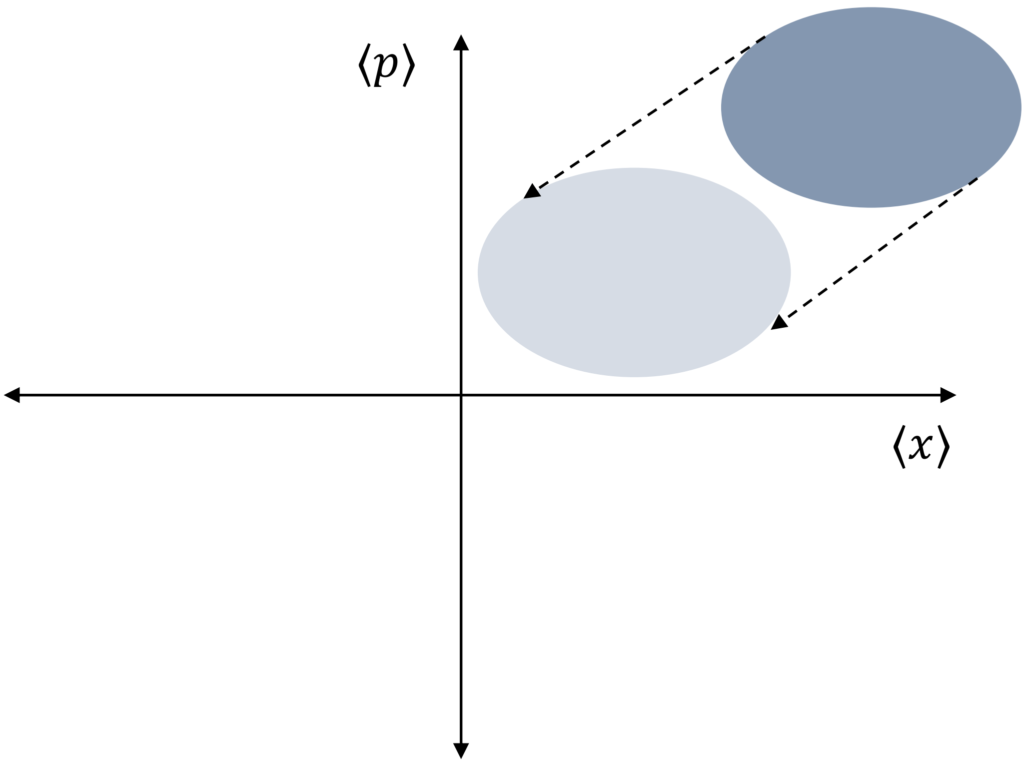
1. Contraction of phase-space displacement: Signal loss



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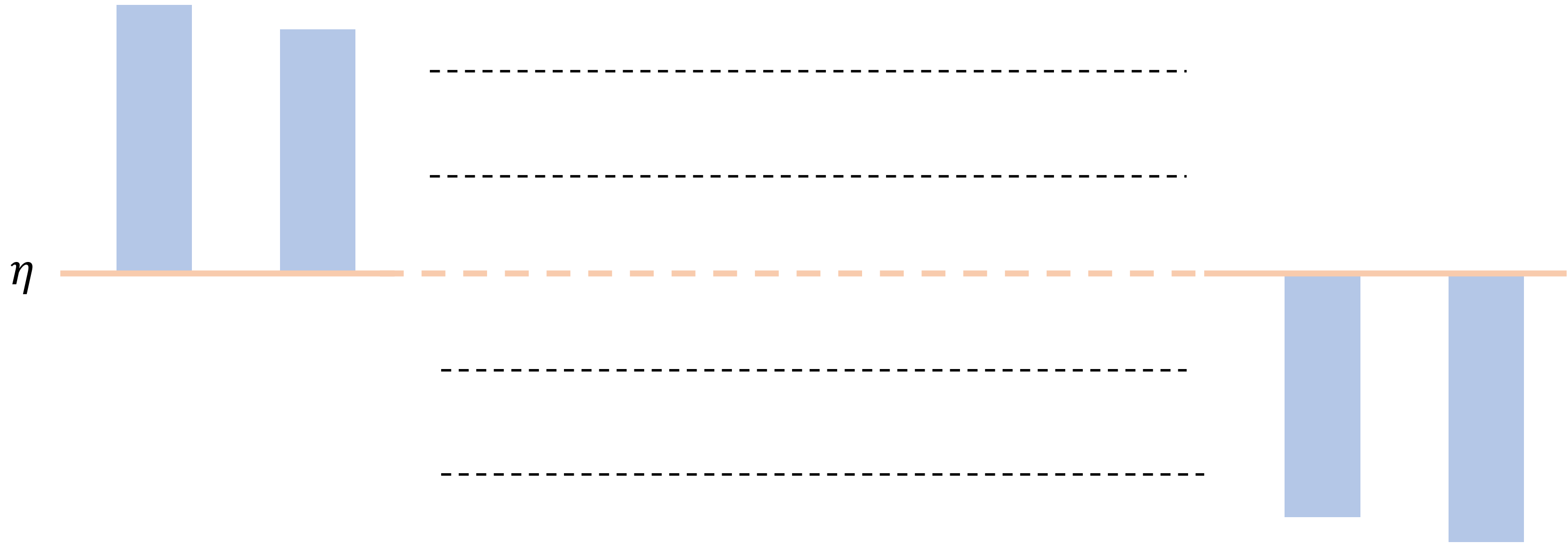

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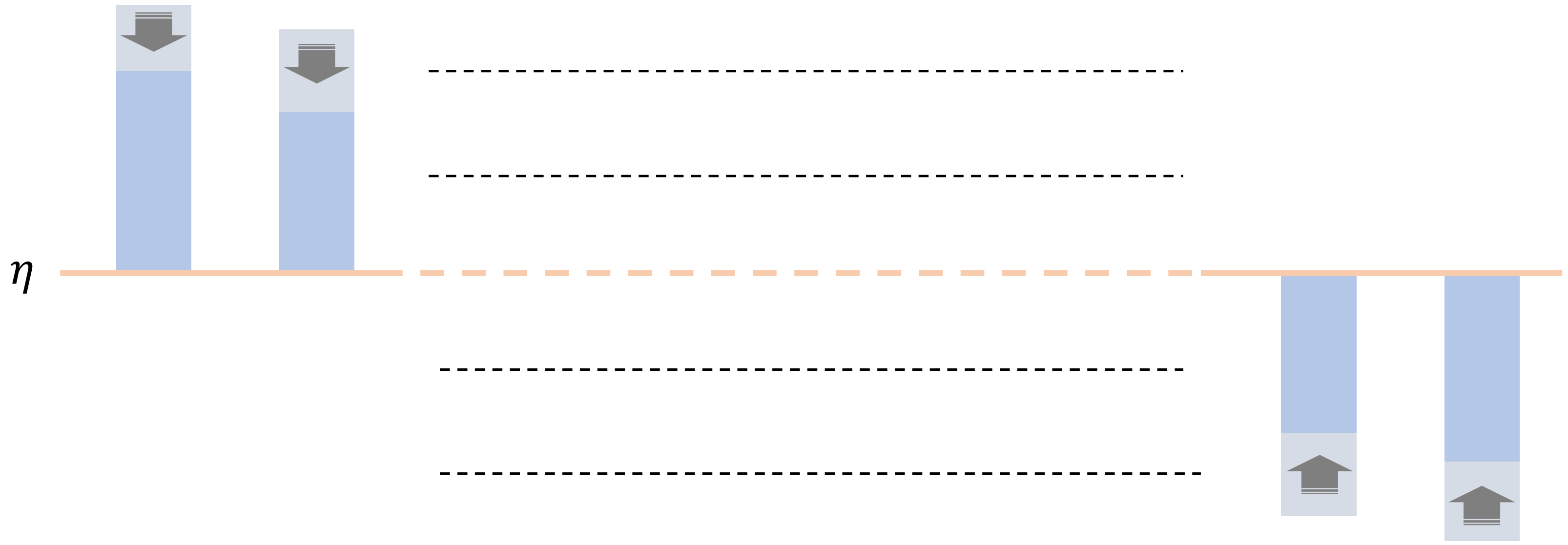

Laws of Gaussian thermodynamics

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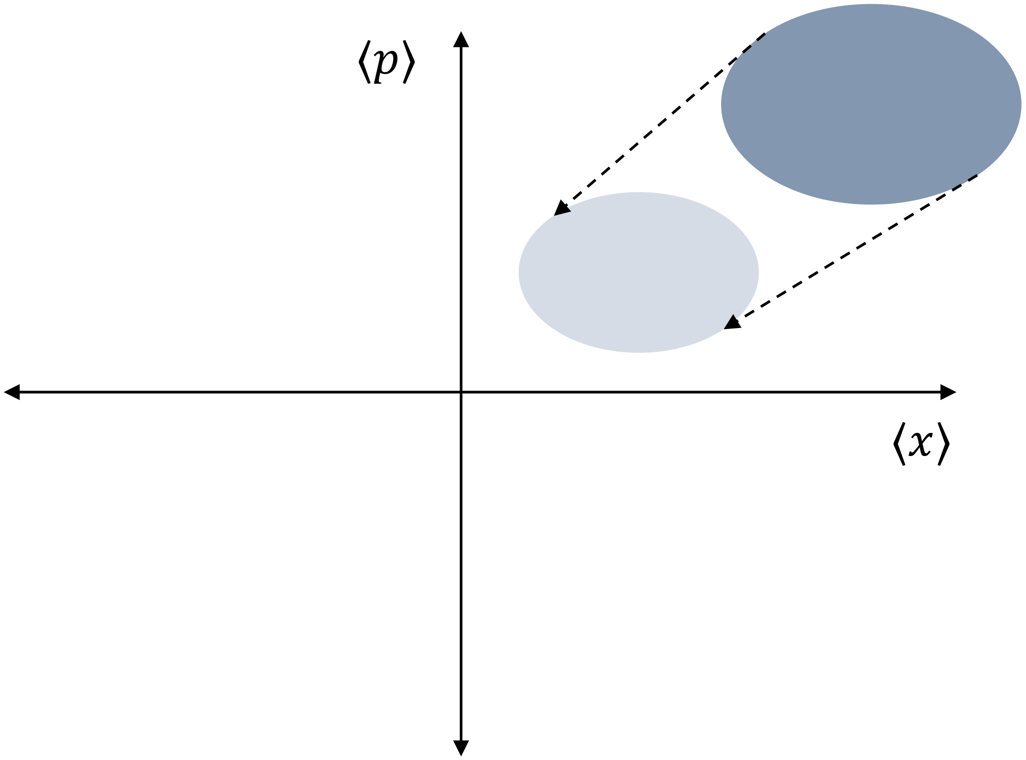
   Quadrature variances can be reduced by Law 2, but loss in signal (Law 1) will overpower this



Laws of Gaussian thermodynamics

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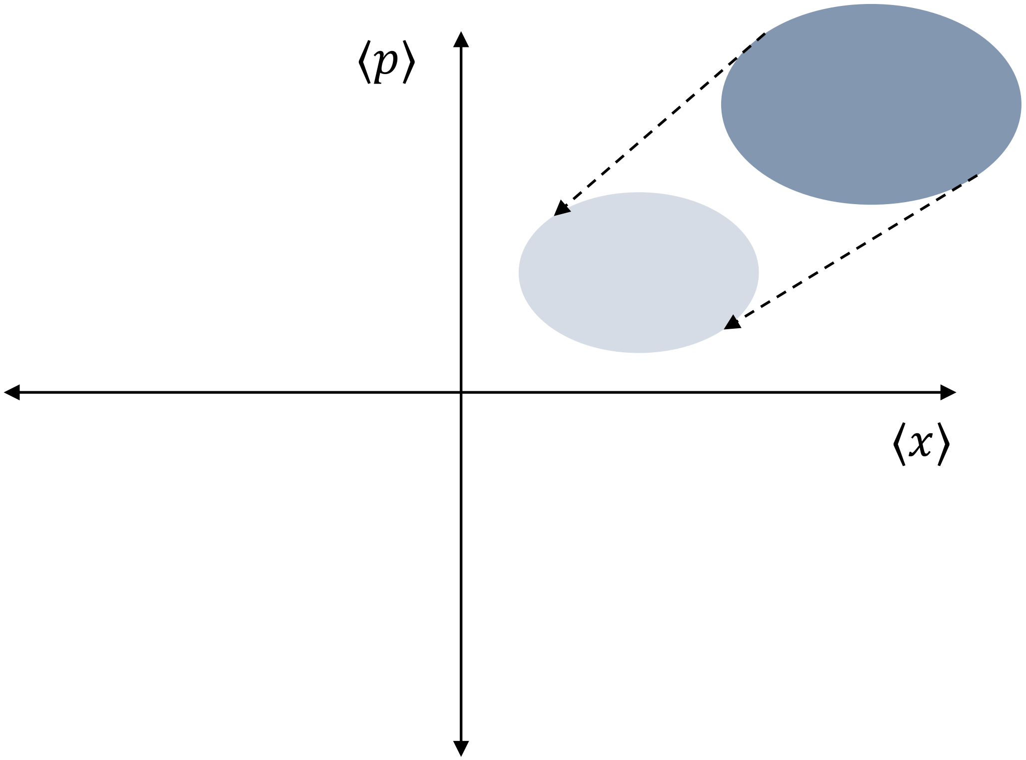

4. More to come…

Outlook

- Laws of thermodynamics on higher-order quadrature moments
- Quantifying the work cost of squeezing, displacement, etc.
- Gaussian thermal engines
- Beyond Gaussian: more general energy-conserving interactions
- Unified understanding of CV resources

Thanks

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Presentation based on

[1] Benjamin Yadin, Felix C. Binder, Jayne Thompson, VN, Mile Gu, and M. S. Kim. **Operational Resource Theory of Continuous-Variable Nonclassicality**. Phys. Rev. X 8, 041038 (2018)

[2] VN, Felix C. Binder, Jayne Thompson, Benjamin Yadin, Syed M. Assad, and Mile Gu. In preparation.

(Independent related work: Kwon et al., arXiv:1804.09355)