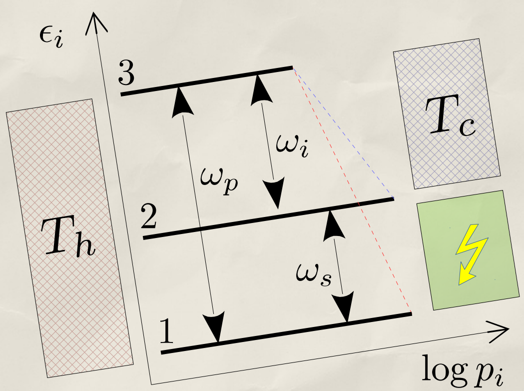
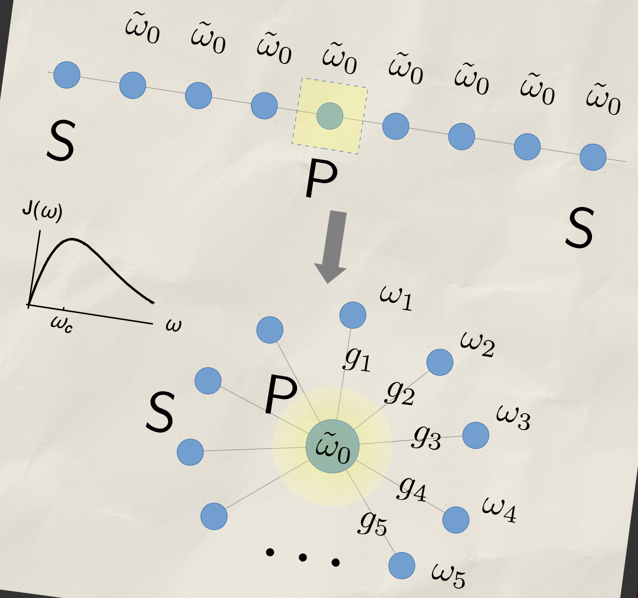
DOUBLE FEATURE!

Quantum thermal engineering



AND

Quantum thermometry



★ ★ ★ ★ ★ ★ ★ KITP USBC 08/06/18 ★ ★ ★ ★ ★ ★ ★

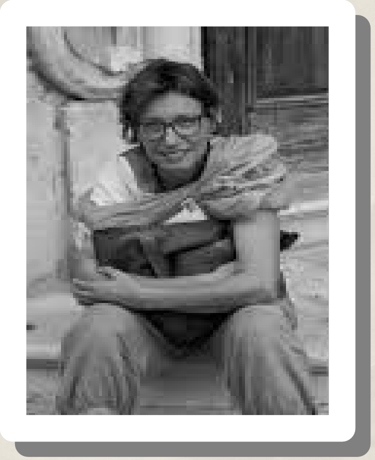
M. Mehboudi, Anna Sanpera, and LAC, *“Quantum thermometry: Topical review”* (in preparation)

QUANTUM THERMOMETRY

University of Nottingham
UK | CHINA | MALAYSIA

LUIS A. CORREA

M. Mehboudi, Anna Sanpera, and LAC, *"Quantum thermometry: Topical review"* (in preparation)



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Gerardo Adesso	University of Nottingham
Christos Charalambous	ICFO
Miguel Ángel García-March	ICFO
Senaida Hernández-Santana	ICFO
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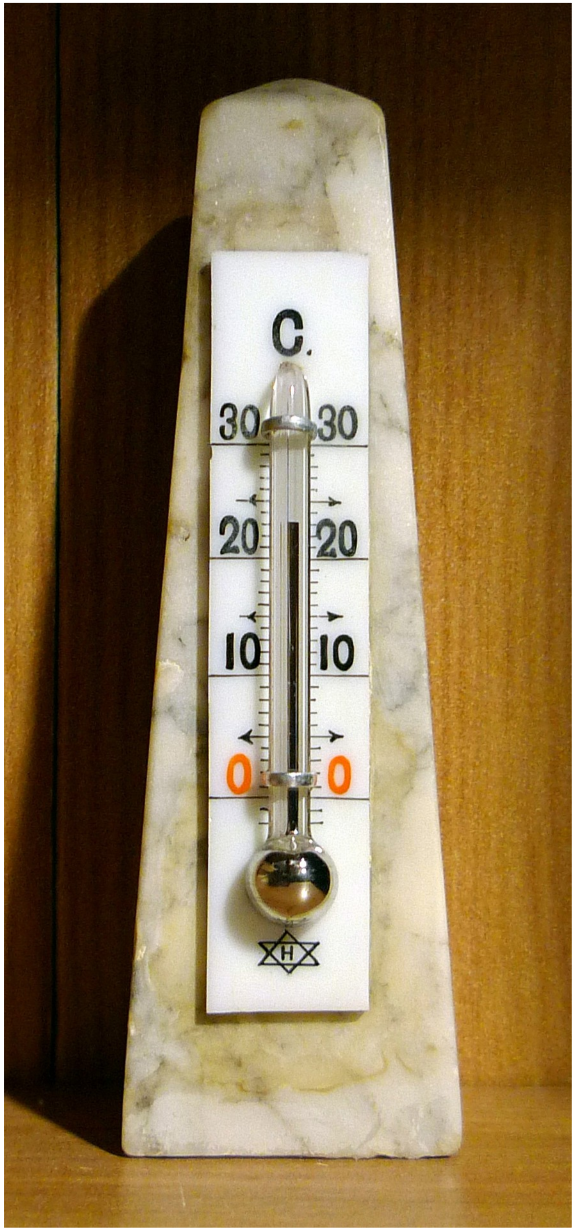
Aniello Lampo	ICFO
Maciej Lewenstein	ICFO
Martí Perarnau-Llobet	Max Planck Institut für Quantenoptik

QUANTUM THERMOMETRY

Estimating temperature for quantum technologies:

- [ ] Nanoscale spatial resolution.
- [ ] Minimally disturbing techniques.
- [ ] High precision at low temperatures.



NANOSCALE THERMOMETRY

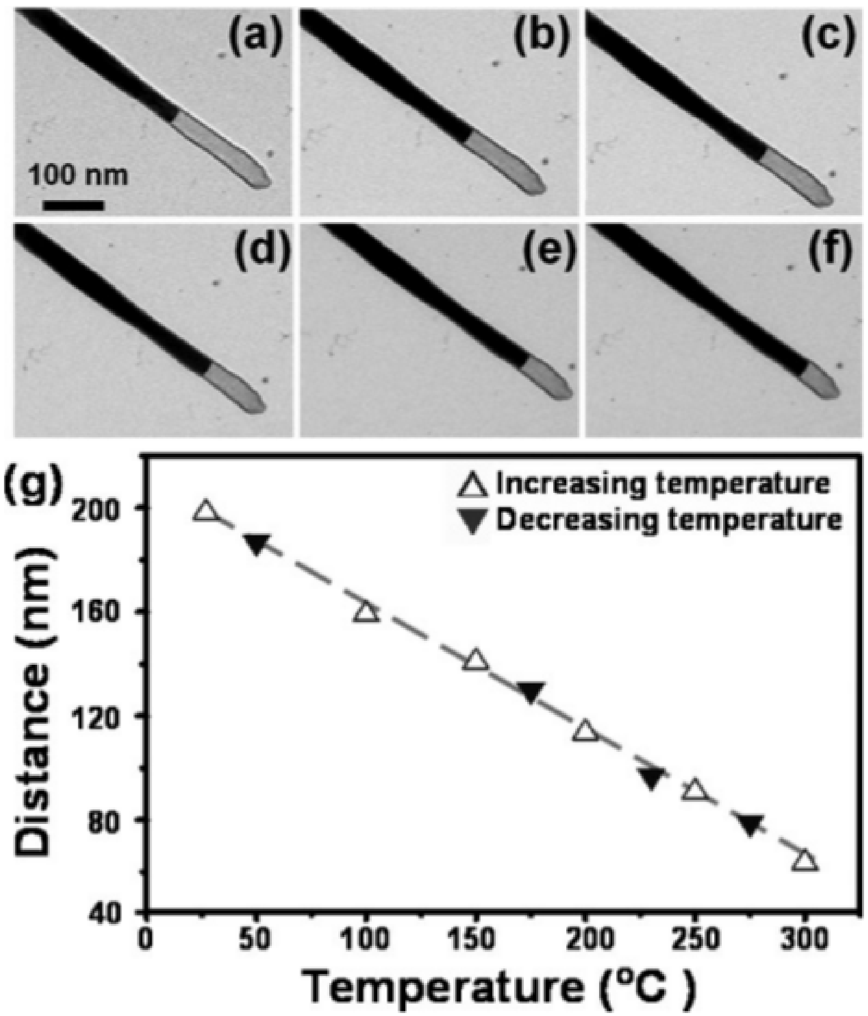


Figure 3. a–f) TEM images of a selected Pb/ZnO nanocable, with Pb filling about 16 µm in length, heated from room temperature to 25, 100, 150, 200, 250, and 300 °C, respectively, recorded by video camera in the transmission electron microscope. g) Plot of cavity length versus heating temperature.

C-Y Wang *et al., Adv. Mater.* **20**, 4789 (2008)

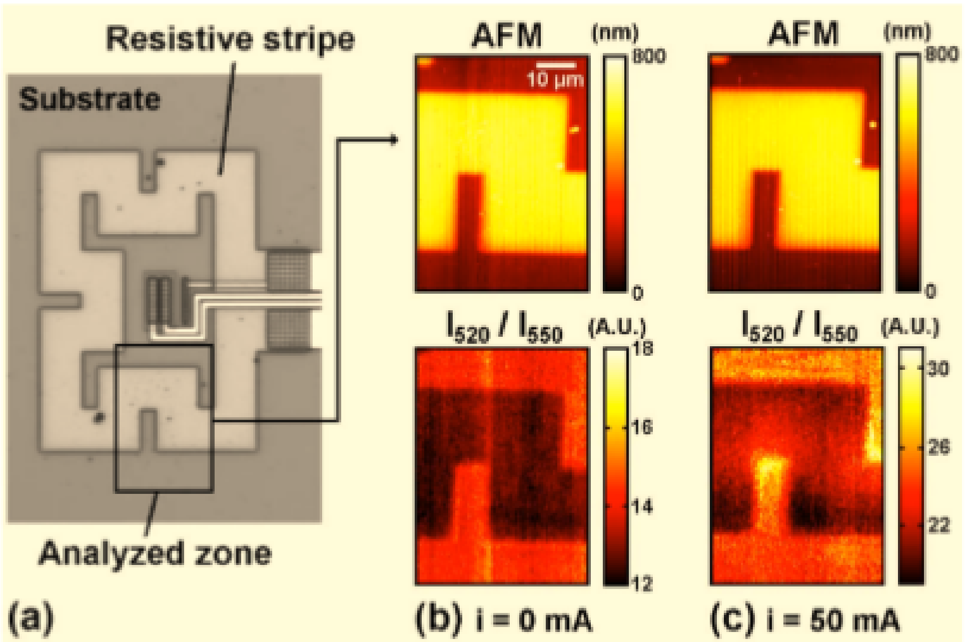


FIG. 3. (Color online) (a) Optical micrograph of the microelectronic circuit; (b) topography and fluorescence ratio images of the structure when no current is passing through the stripe; (c) topography and fluorescence ratio images when a current of ~50 mA is passing through the structure. The bright (hot) zones are clearly visible on the stripe. The image size is 45 $\times 60\ \mu m^2$.

L. Aigouy *et al., Appl. PhLeadys. Lett.* **87**, 184105 (2005)

QUANTUM THERMOMETRY

Estimating temperature for quantum technologies:

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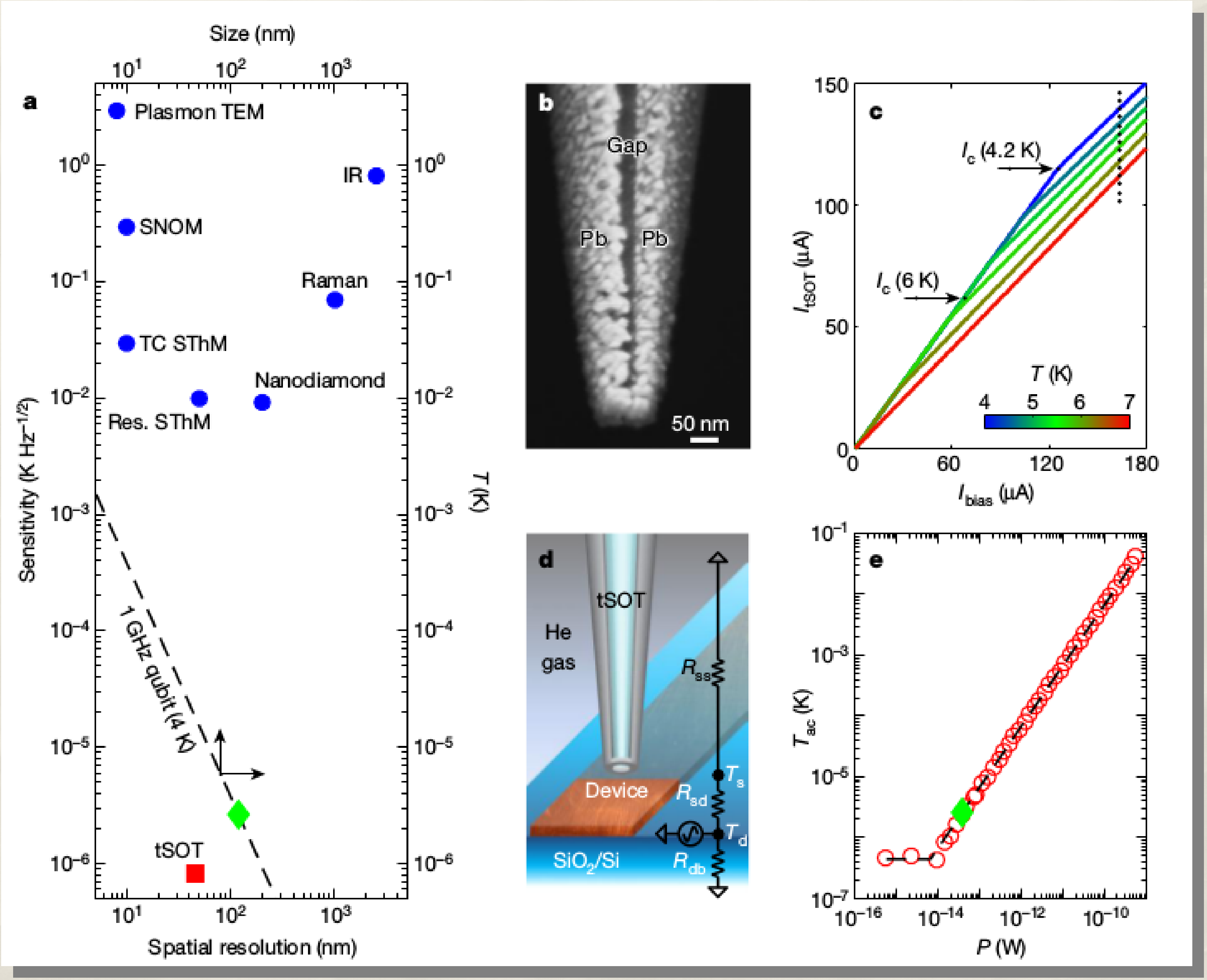
- [ ] High precision at low temperatures.

TOWARDS QUANTUM THERMOMETRY...

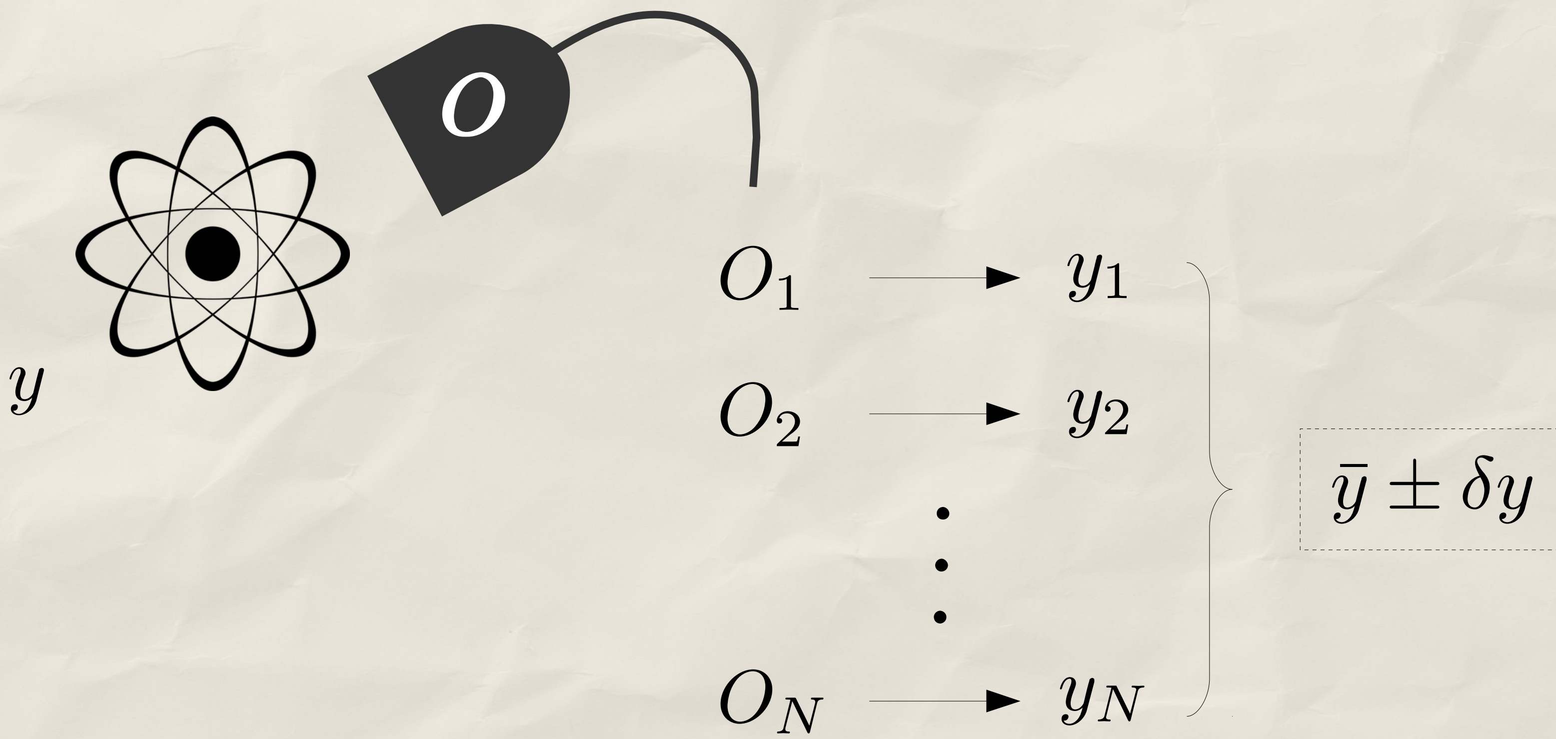


D. Halbertal *et al.*, *Nature* (London) **539**, 407 (2016)

OUTLINE

1. ~~Motivation~~
2. Thermal sensitivity
3. Equilibrium quantum thermometry
4. Quantum thermometry out of equilibrium
5. Low-tempreature scaling of thermal sensitivity

QUANTUM ESTIMATION THEORY



$y = \bar{y}$

$N \to \infty$

$$\delta y \geq \frac{1}{\sqrt{N \mathcal{F}_y(\boldsymbol{O})}}$$

Cramér-Rao bound

QUANTUM ESTIMATION THEORY

$$\frac{\partial_y \langle \boldsymbol{O} \rangle}{\Delta \boldsymbol{O}} \leq \mathcal{F}_y(\boldsymbol{O}) \leq F_y \equiv \sup_{\boldsymbol{O}} \mathcal{F}_y(\boldsymbol{O})$$

Error propagation formula

Classical Fisher information

Quantum Fisher information

$$y = \bar{y}$$

$$N \to \infty$$

$$\delta y \geq \frac{1}{\sqrt{N \mathcal{F}_y(\boldsymbol{O})}}$$

Cramér-Rao bound

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SENSITIVITY AND HEAT CAPACITY

$$\boldsymbol{\varrho}_T = \mathcal{Z}^{-1} e^{-\boldsymbol{H}/T}$$

$$F_T(\boldsymbol{\varrho}_T) = \frac{(\Delta \boldsymbol{H})^2}{T^4}$$

$$C(T) \equiv \frac{d\langle \boldsymbol{H} \rangle}{dT} = \frac{(\Delta \boldsymbol{H})^2}{T^2}$$

$$F_T(\boldsymbol{\varrho}_T) = \frac{C(T)}{T^2}$$

T. Jahnke *et al.*, *PRE* **83**, 011109 (2011)

LAC et al., *PRL* **114**, 220405 (2015)

SENSITIVITY AND HEAT CAPACITY

$$\Delta T \leq \frac{1}{\sqrt{F_T(\boldsymbol{\varrho}_T)}}$$

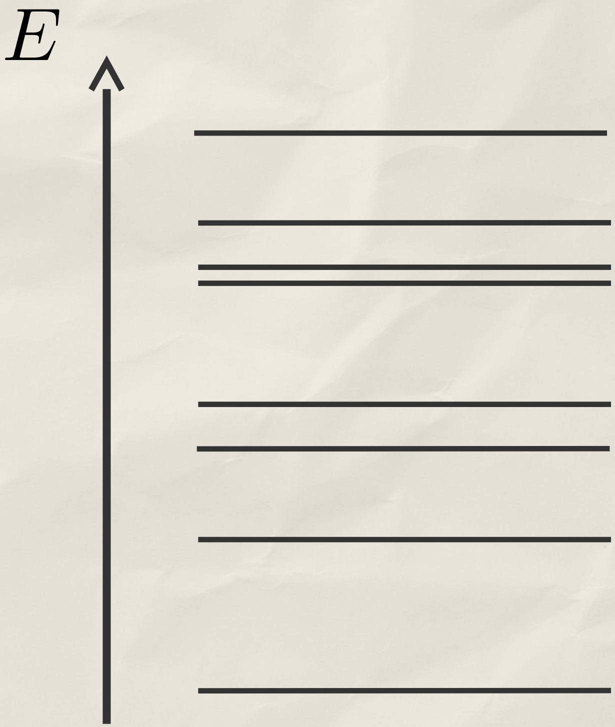
$$F_T(\boldsymbol{\varrho}_T) = \frac{C(T)}{T^2}$$

$$\left(\frac{T}{\Delta T}\right)^2 \leq C(T)$$

T. Jahnke *et al.*, *PRE* **83**, 011109 (2011)

LAC et al., *PRL* **114**, 220405 (2015)

THE BEST EQUILIBRIUM THERMOMETER



$$\partial_{\epsilon_i} \Delta \boldsymbol{H} = 0$$

Reeb & Wolf, *IEEE Trans. Inf. Theor.*, 1458 (2015)

LAC et al., *PRL* **114**, 220405 (2015)

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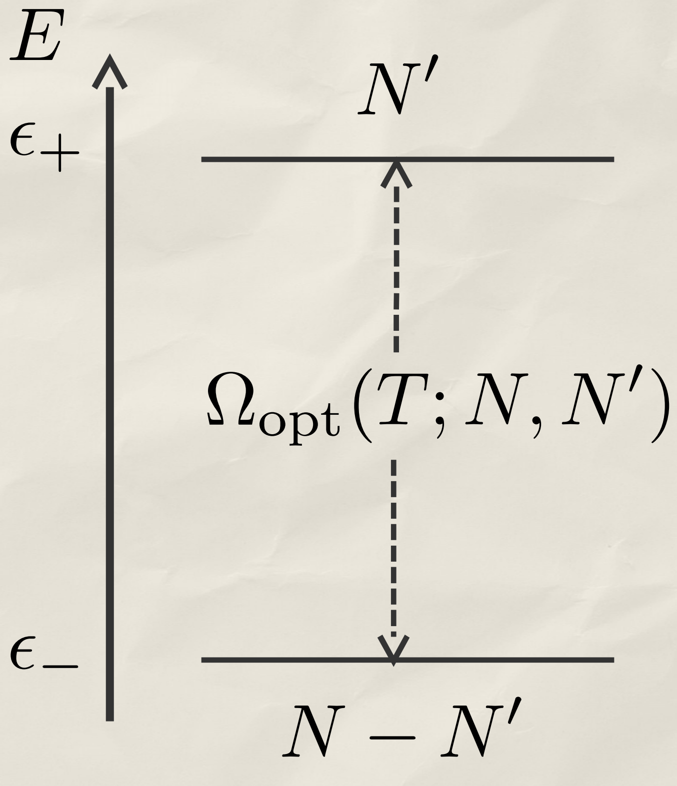

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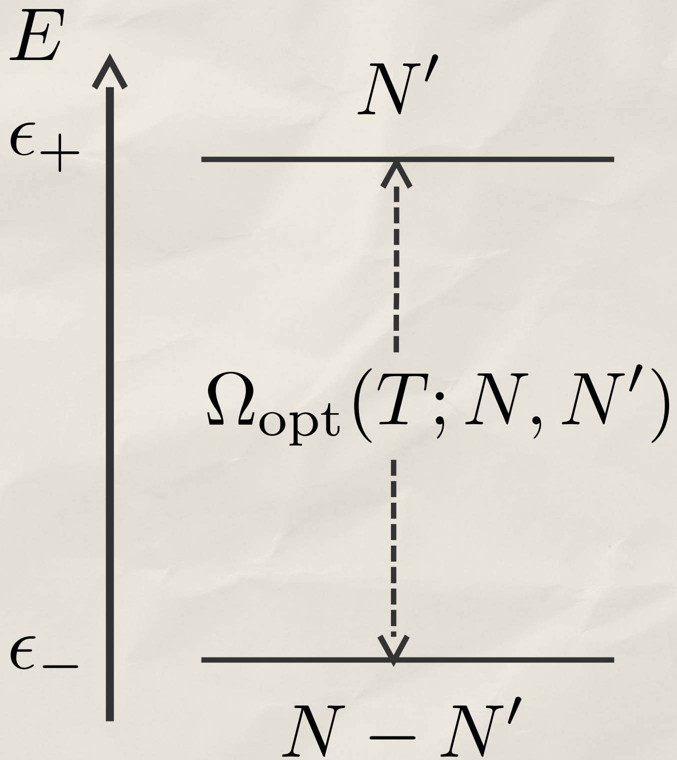
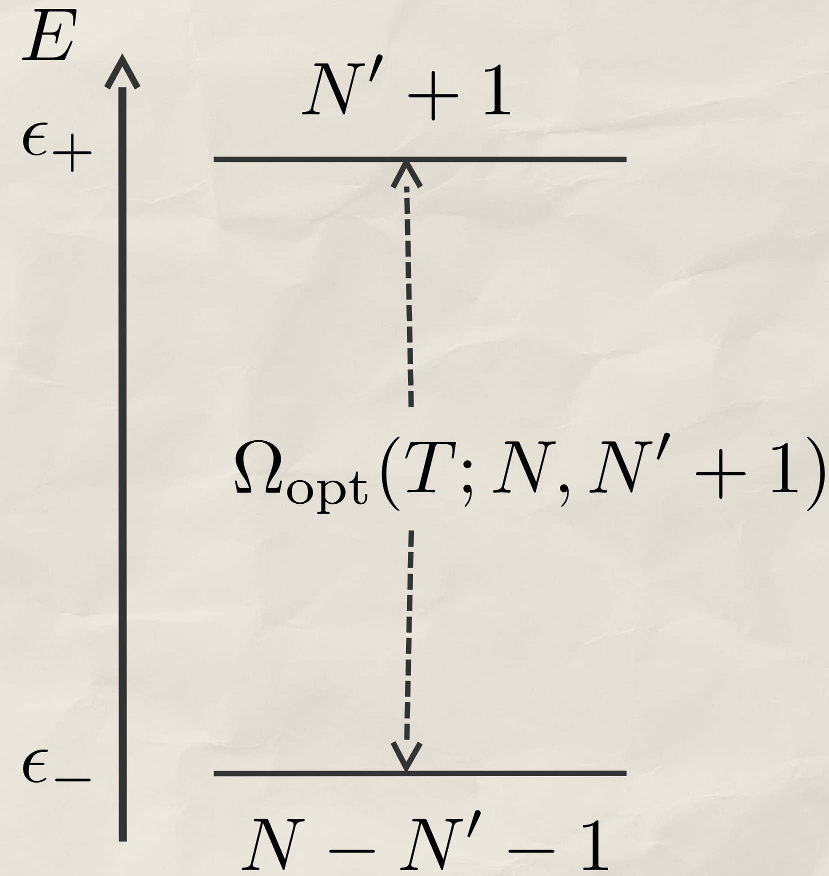


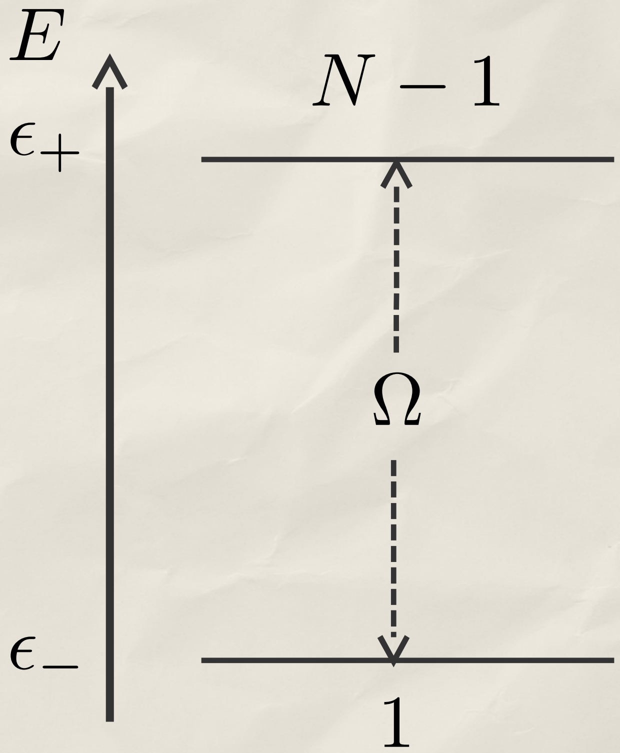


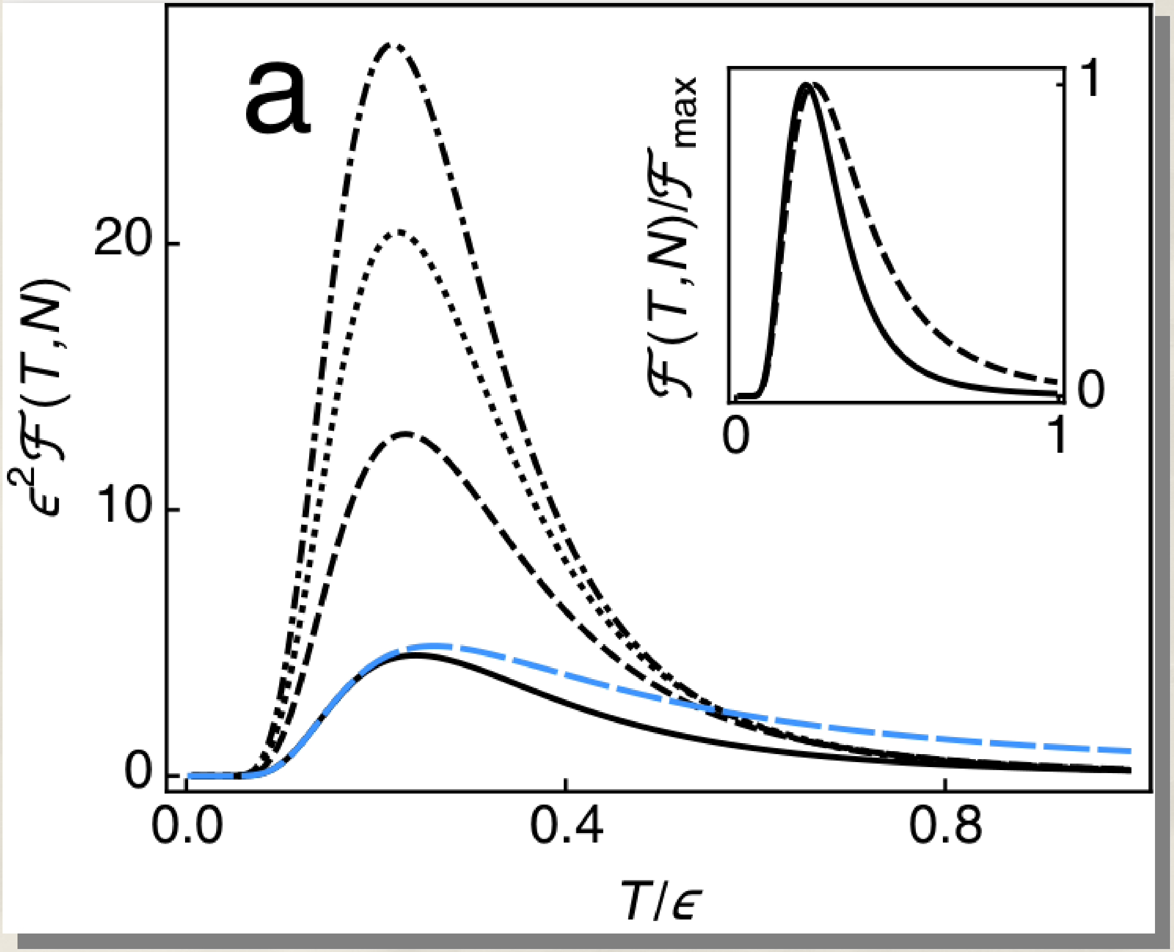
$$C(T; N, N') \leq C(T; N, N' + 1)$$

Reeb & Wolf, *IEEE Trans. Inf. Theor.*, 1458 (2015)

LAC et al., *PRL* **114**, 220405 (2015)

THE BEST EQUILIBRIUM THERMOMETER





LAC et al., *PRL* **114**, 220405 (2015)

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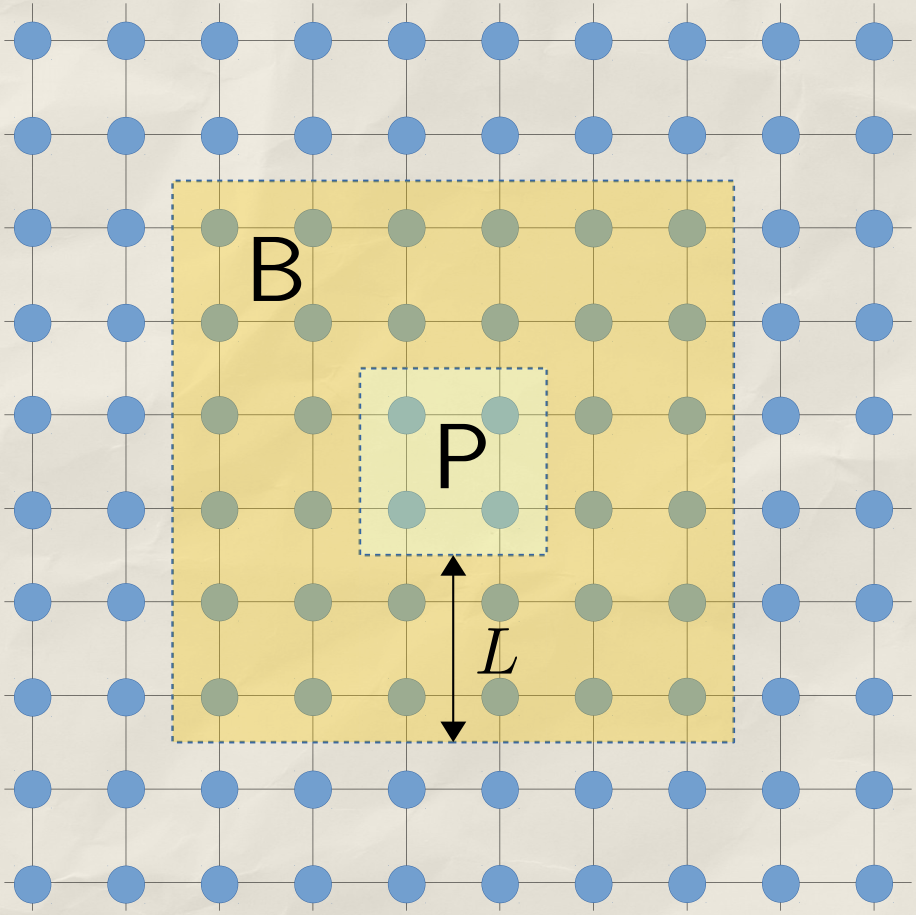
SENSITIVITY AND LOCAL HEAT CAPACITY



- $|\mathsf{B}(L)| \ll |\mathsf{P}|$
- $L > 2\xi(T)$
- $T > T^*$

$$F_T(\mathrm{tr}_{\mathsf{S}}\, \boldsymbol{\varrho}_T) \simeq \frac{(\Delta \boldsymbol{H}_{\mathsf{P}})^2}{T^4}$$

A. De Pasquale *et al.*, *Nat. Commun.* **7**, 12782 (2016)

G. De Palma *et al.*, *PRA* **95**, 052115 (2017)

SENSITIVITY AND DRESSED HAMILTONIAN

$$\mathcal{Z}_{\mathsf{P}}^{*} \equiv \frac{\operatorname{tr} e^{-\beta(\boldsymbol{H}_{\mathsf{P}}+\boldsymbol{H}_{\mathsf{S}}+\boldsymbol{H}_{\text{int}})}}{\operatorname{tr} e^{-\beta \boldsymbol{H}_{\mathsf{S}}}}$$

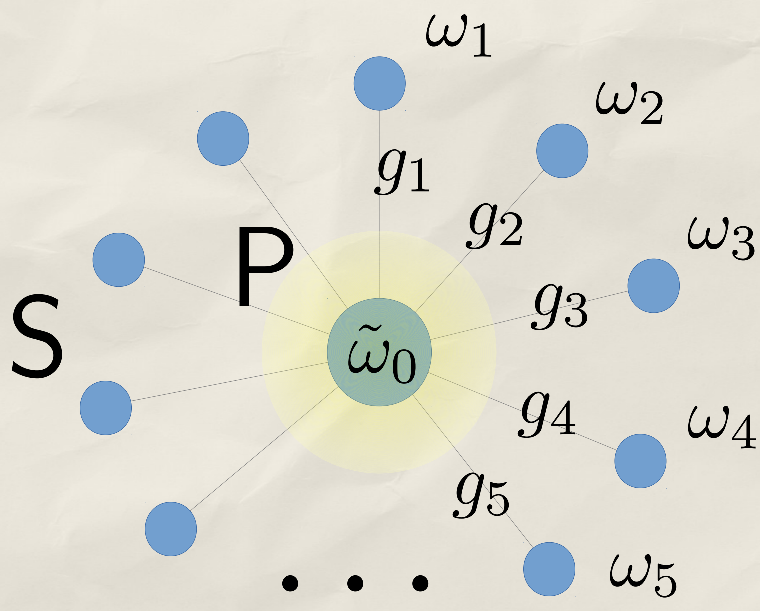
$$-\partial_{\beta} \log \mathcal{Z}_{\mathsf{P}}^{*} = U_{\mathsf{P}}(T) = \langle \boldsymbol{E}_{\mathsf{P}}^{*}(T) \rangle$$

$$Q(\operatorname{tr}_{\mathsf{S}} \boldsymbol{\varrho}_T, \boldsymbol{E}_{\mathsf{P}}^{*}(T)) \equiv -\frac{1}{2} \int_0^1 da \operatorname{tr}\left\{[\boldsymbol{E}_{\mathsf{P}}^{*}, \operatorname{tr}_{\mathsf{S}} \boldsymbol{\varrho}_T^{a}][\boldsymbol{E}_{\mathsf{P}}^{*}(T), \operatorname{tr}_{\mathsf{S}} \boldsymbol{\varrho}_T^{1-a}]\right\}$$

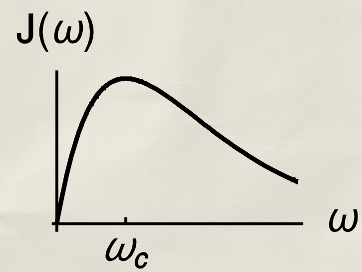
$$F_T(\operatorname{tr}_{\mathsf{S}} \boldsymbol{\varrho}_T) = \frac{(\Delta \boldsymbol{E}_{\mathsf{P}}^{*})^2 - Q(\operatorname{tr}_{\mathsf{S}} \boldsymbol{\varrho}_T, \boldsymbol{E}_{\mathsf{P}}^{*})}{T^4}$$

H. Miller & J. Anders, *arXiv:1801.08057*

SENSITIVITY ENHANCED BY DISSIPATION



$$J(\omega) \equiv \pi \sum_\mu \frac{g_\mu^2}{2m_\mu \omega_\mu} \delta(\omega - \omega_\mu)$$

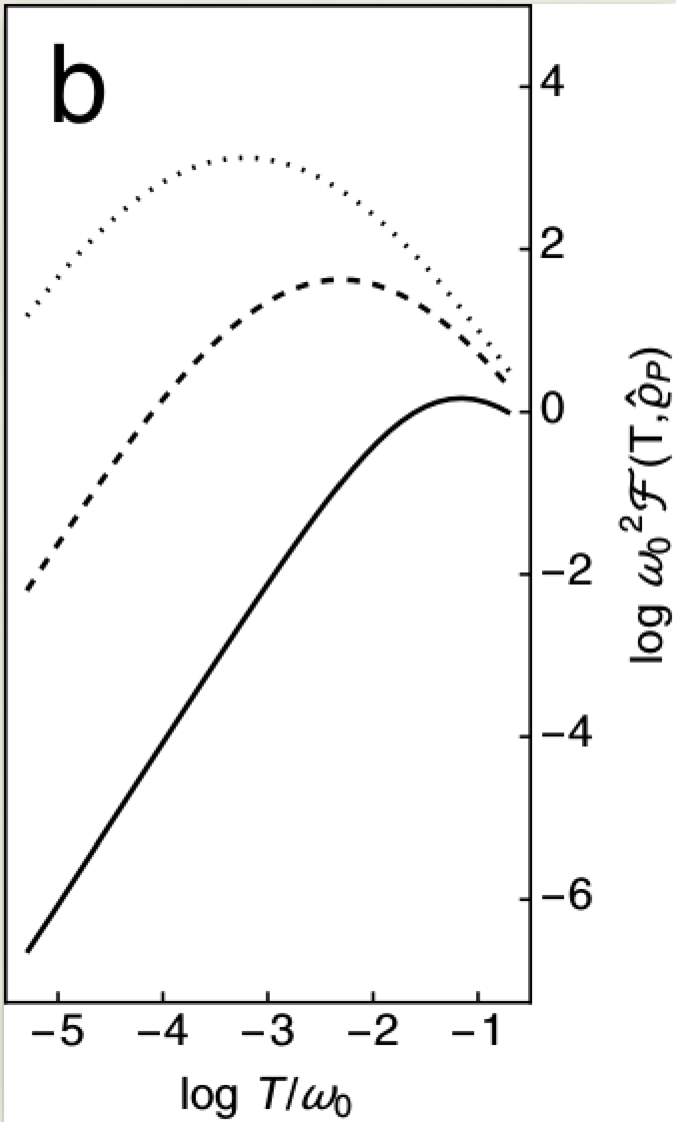


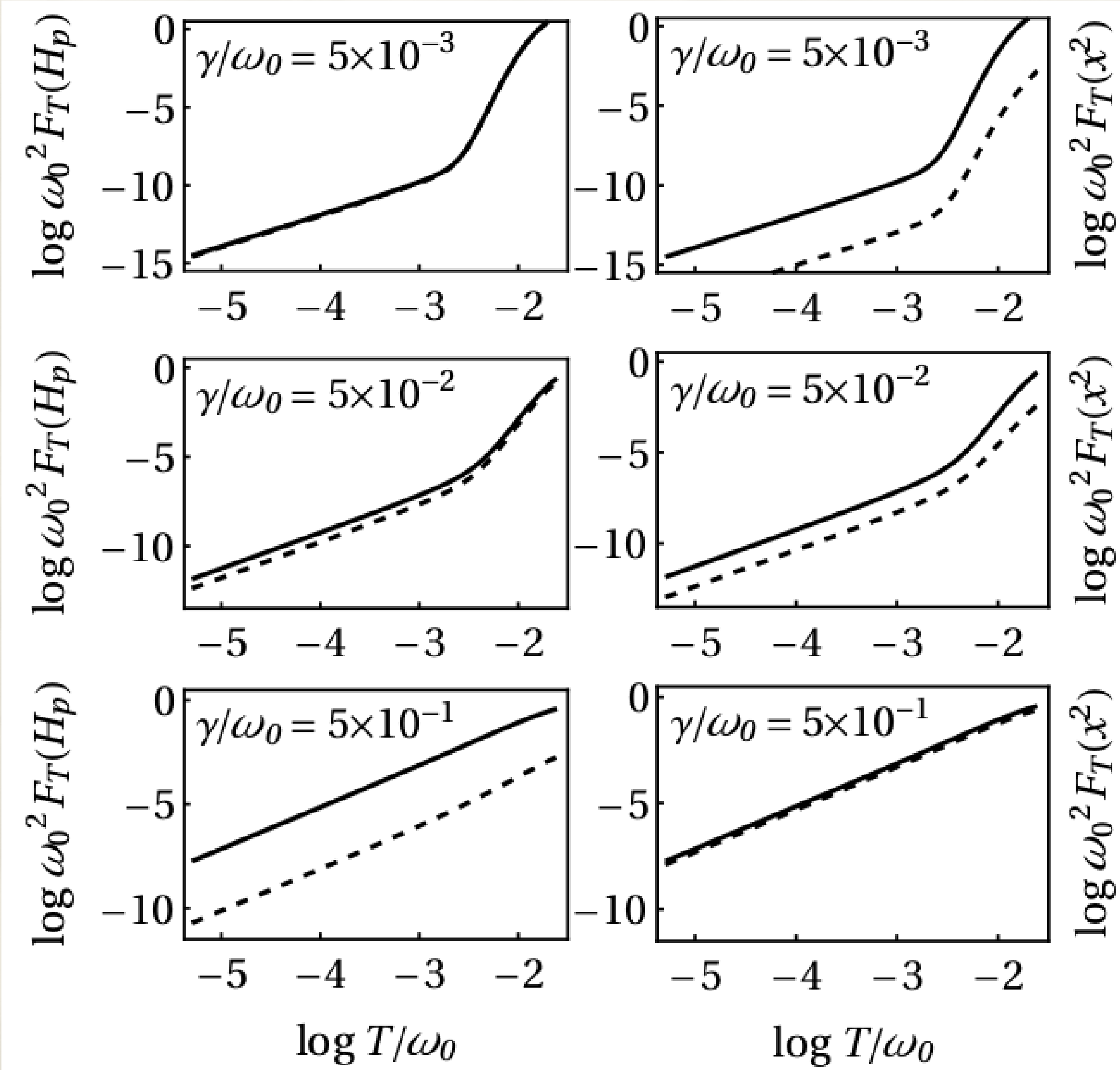
$$\ddot{x}(t) + \tilde{\omega}_0^2 x(t)^2 - x(t) \star \chi(t) = F(t)$$

Quantum Langevin equation

LAC *et al.*, *PRA* **96**, 062103 (2017)

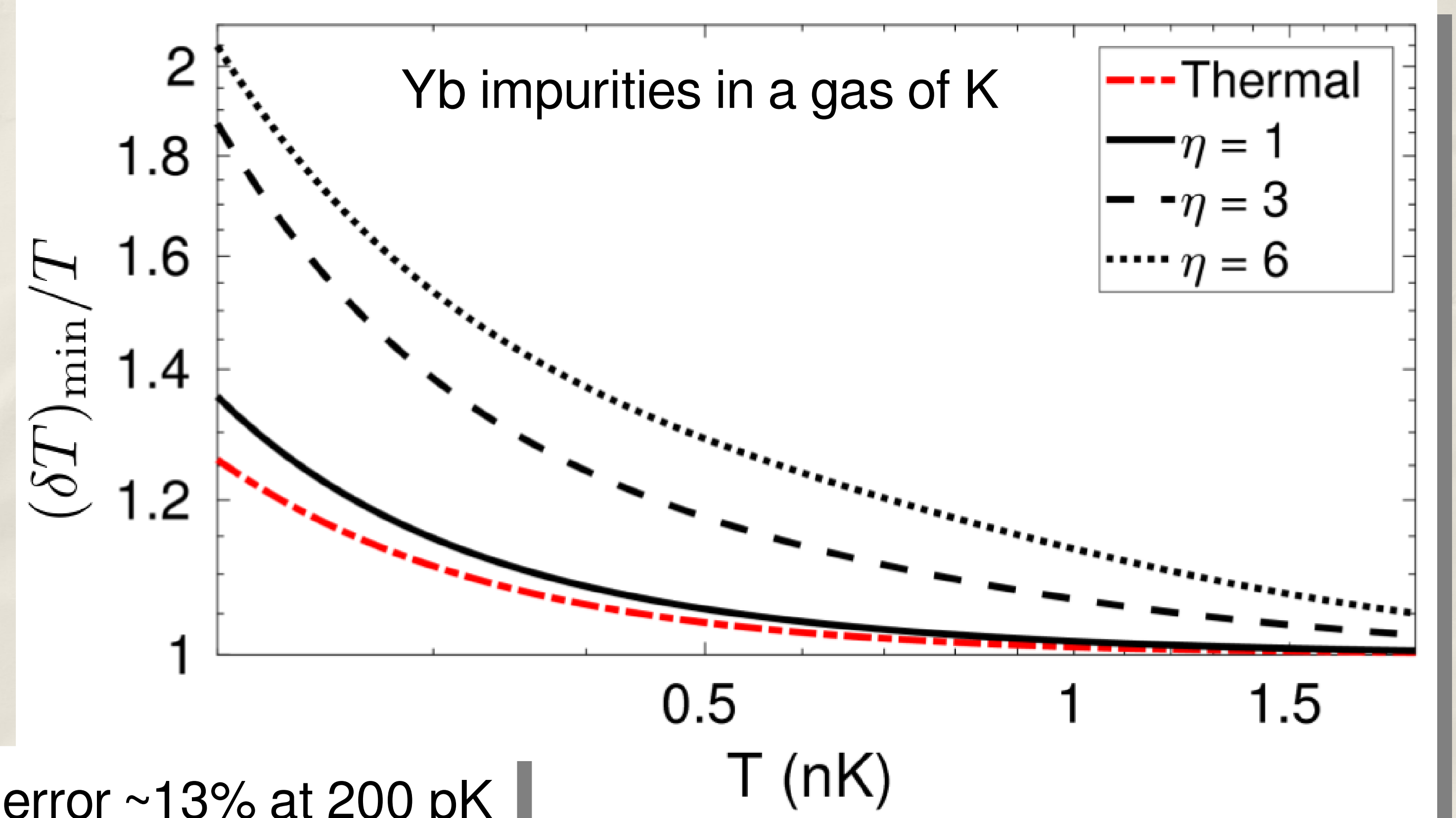
SENSITIVITY ENHANCED BY DISSIPATION





LAC *et al.*, *PRA* **96**, 062103 (2017)

POLARON THERMOMETRY IN A BEC



Relative error ~13% at 200 pK
with 100 measurements !

$$N = 5000$$
$$\omega_B = 200\pi \text{ Hz}$$

A. Lampo *et al.*, *arXiv:1803.08946* (2018)

M. Mehboudi *et al.*, (in preparation)

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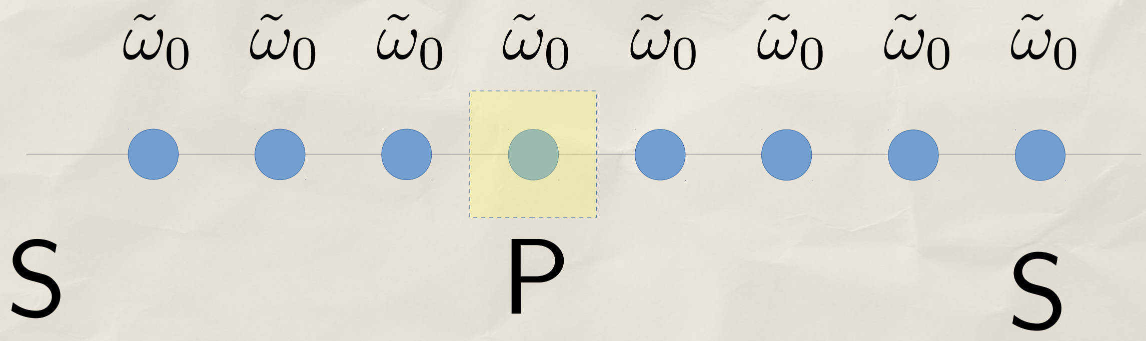
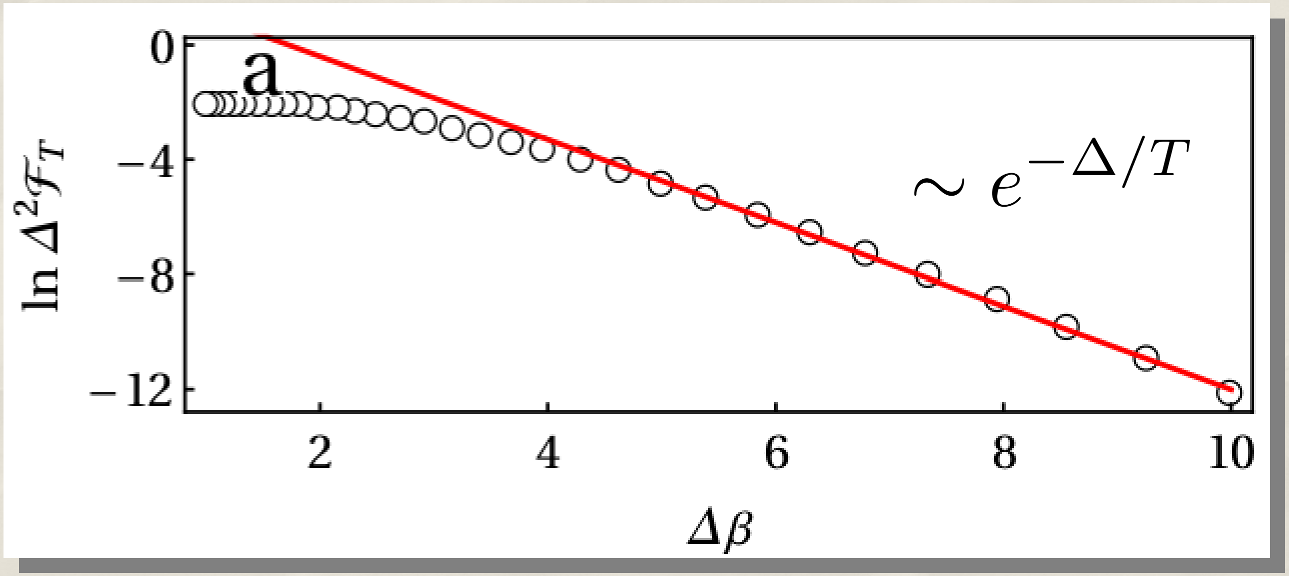
GAPPED VS. GAPLESS

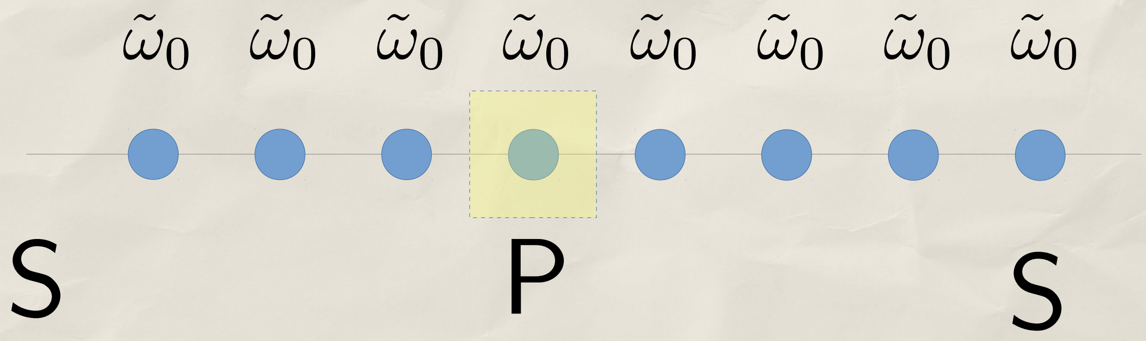


Gapped translationally invariant harmonic chain

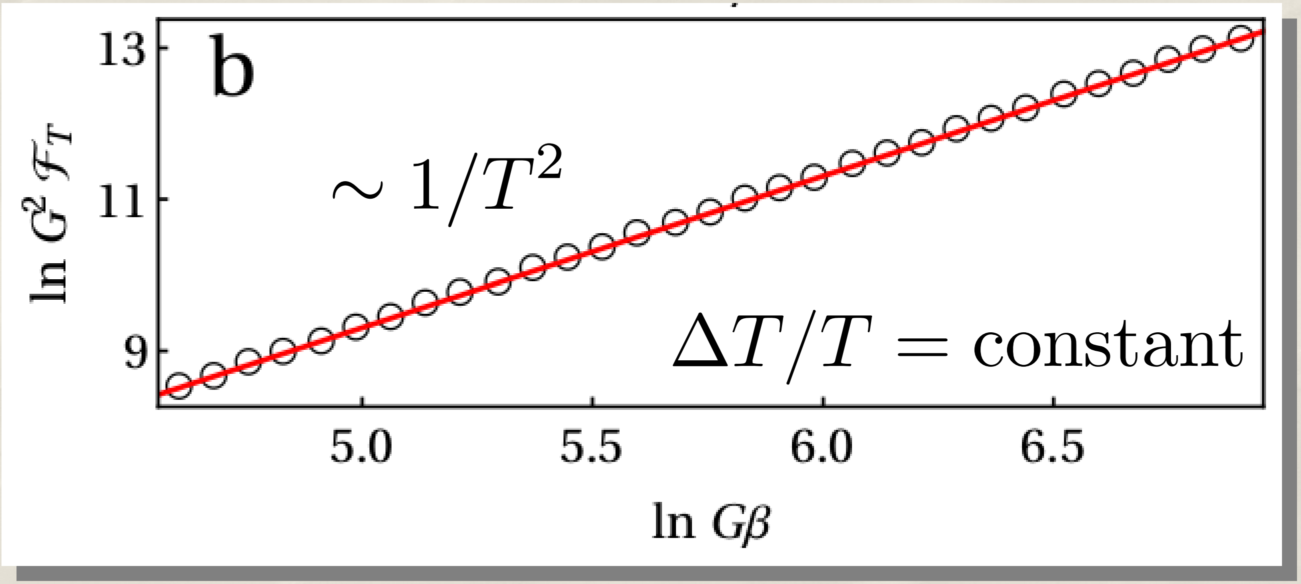


K. V. Hovhannisyan and LAC, *arXiv:1712.03088*

GAPPED VS. GAPLESS

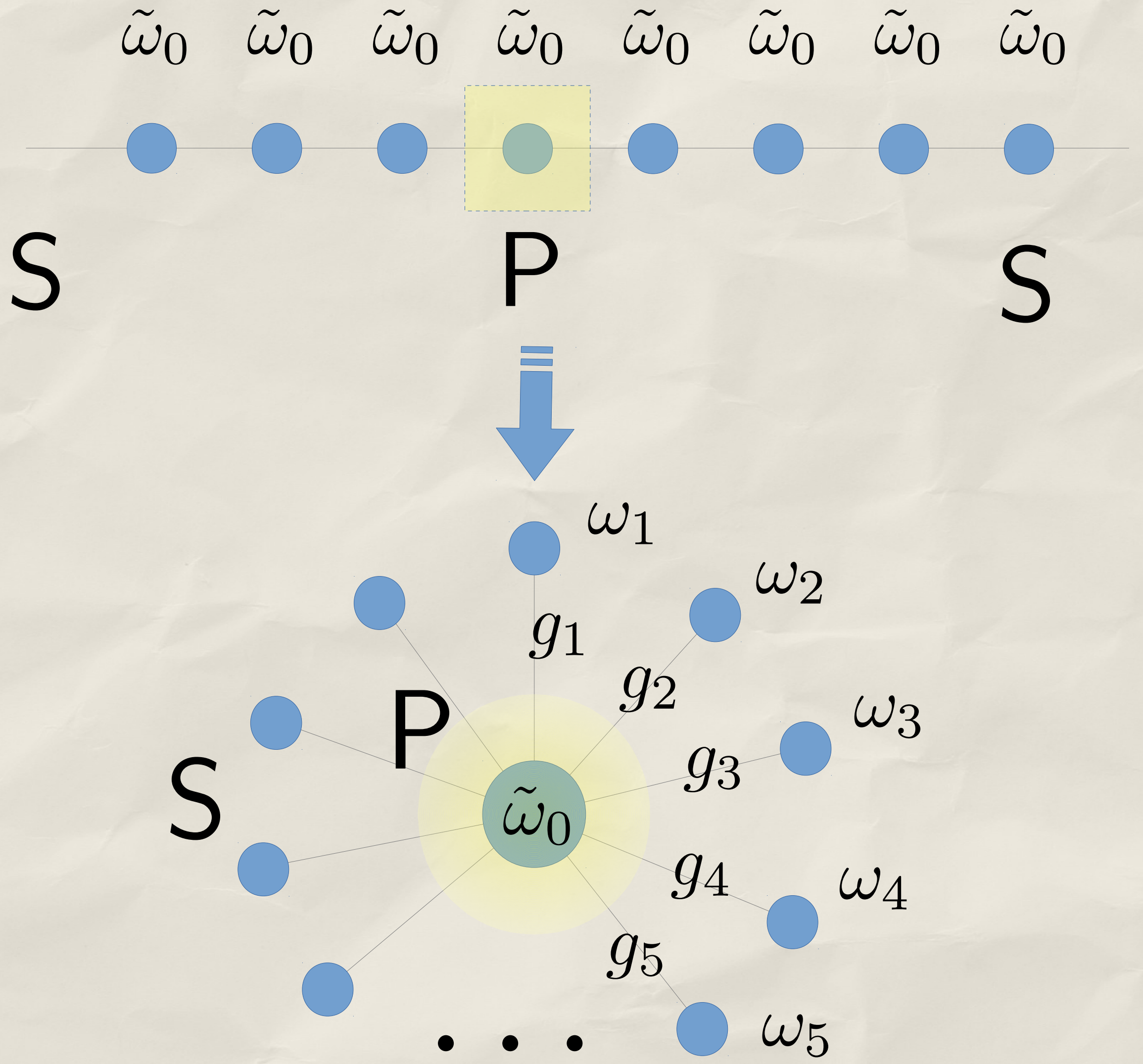


Gapless translationally invariant harmonic chain



K. V. Hovhannisyan and LAC, *arXiv:1712.03088*

AN OPEN SYSTEM APPROACH



K. V. Hovhannisyan and LAC, *arXiv:1712.03088*

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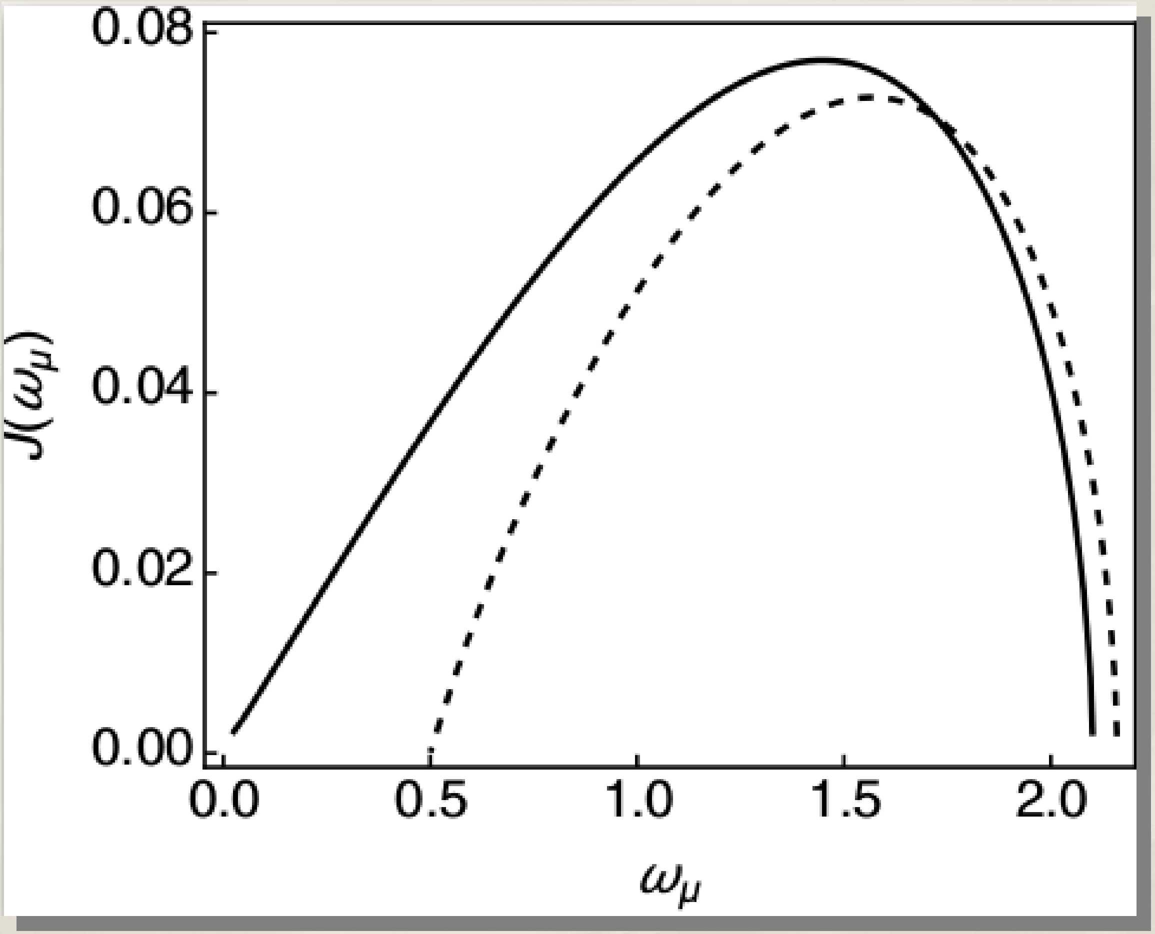

K. V. Hovhannisyan and LAC, *arXiv:1712.03088*

WRAP-UP

Equilibrium quantum thermometry

* The heat capacity places the ultimate bound on thermometric precision.
* Sub-optimal probes can prove versatile.

Non equilibrium quantum thermometry

* Dissipation can be exploited as a resource at low T.
* The bose-polaron model is a good platform to study precise non-demolition thermometry on a BEC.

Low-temperature thermometry

* Local thermometry in a many-body system can be exponentially or polynomially inefficient, depending on whether or not the system is gapped.