Adaptive, symmetry-informed Bayesian metrology for precise quantum technology measurements

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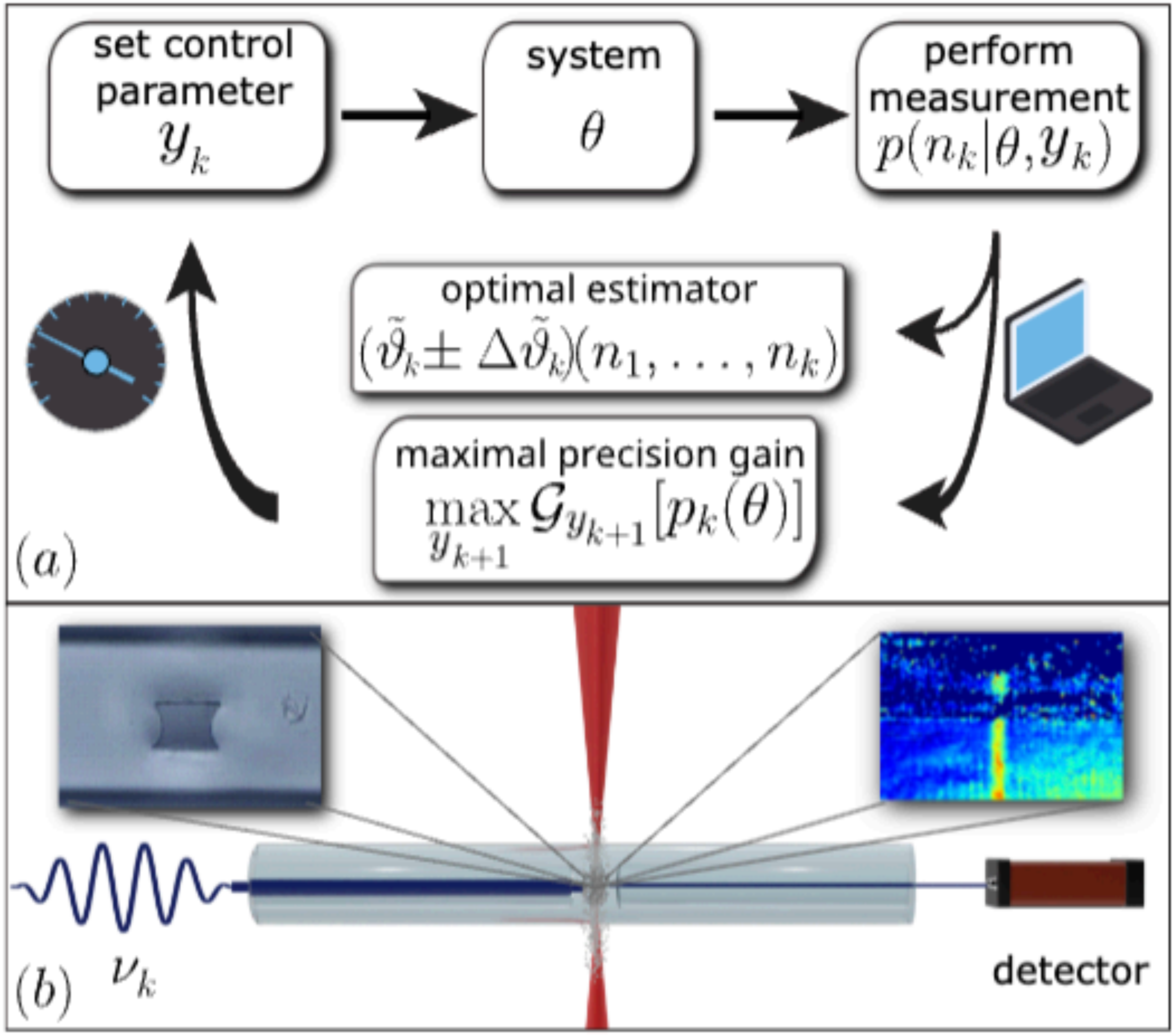
Outline

- Experimental atom-number estimation:
  - Atom-photon interface
  - Optimal strategy: estimator, uncertainty, and gain
  - Platform symmetries and location-isomorphic parameters
  - Symmetry-informed quantum sensing
  - Adaptive protocol and results
- Outlook: Bayesian multiparameter estimation

Adaptive Bayesian atom-number estimation



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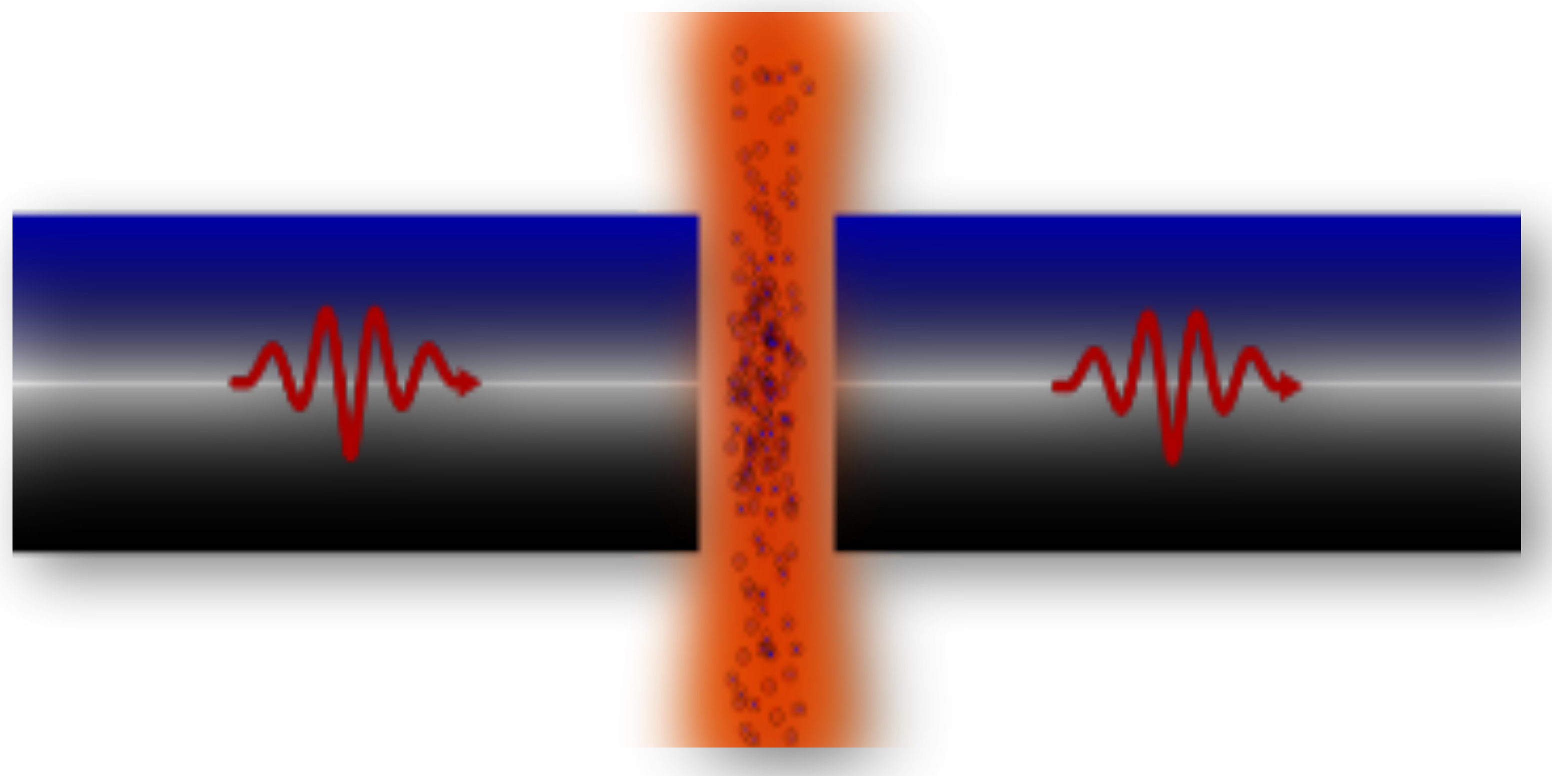
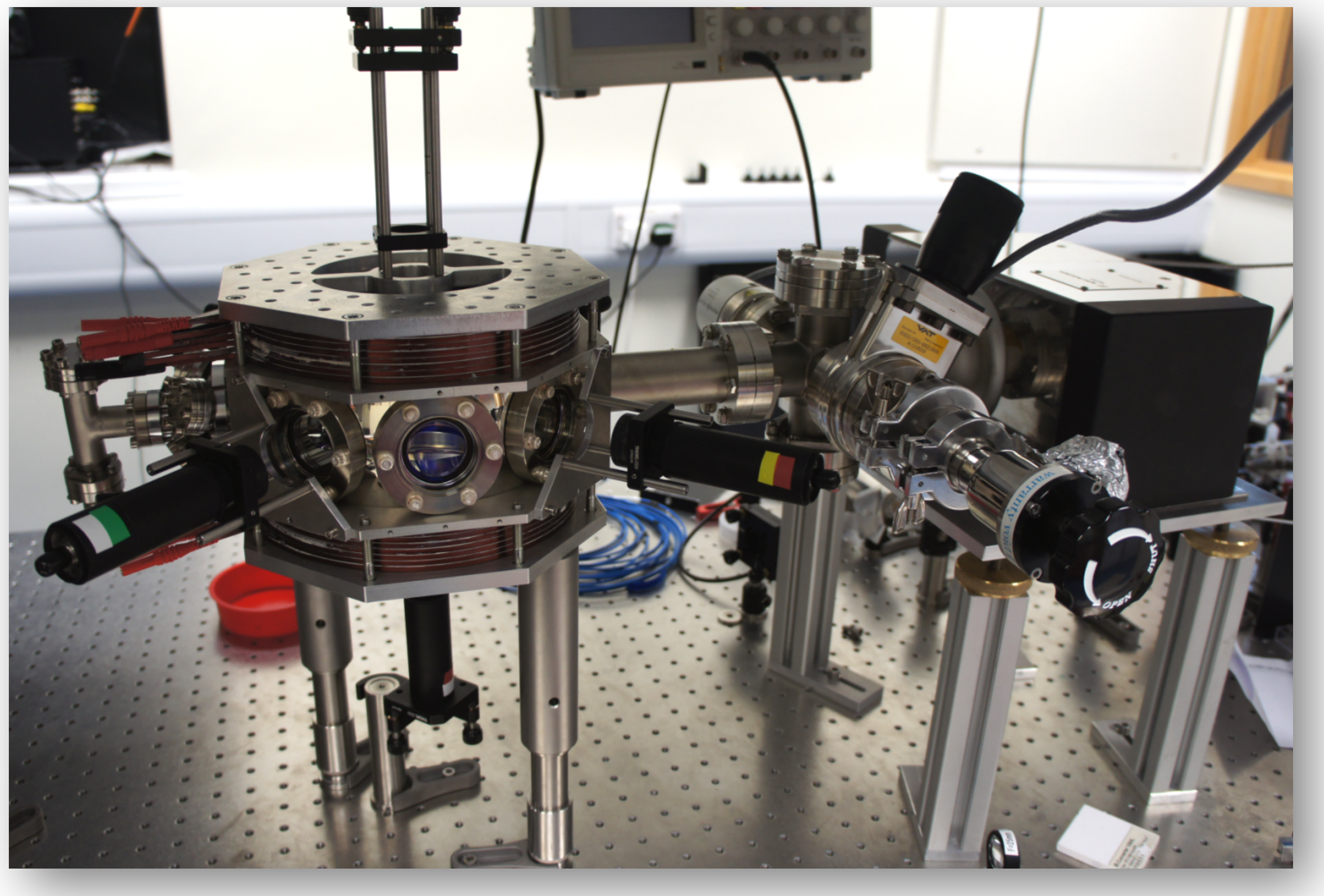
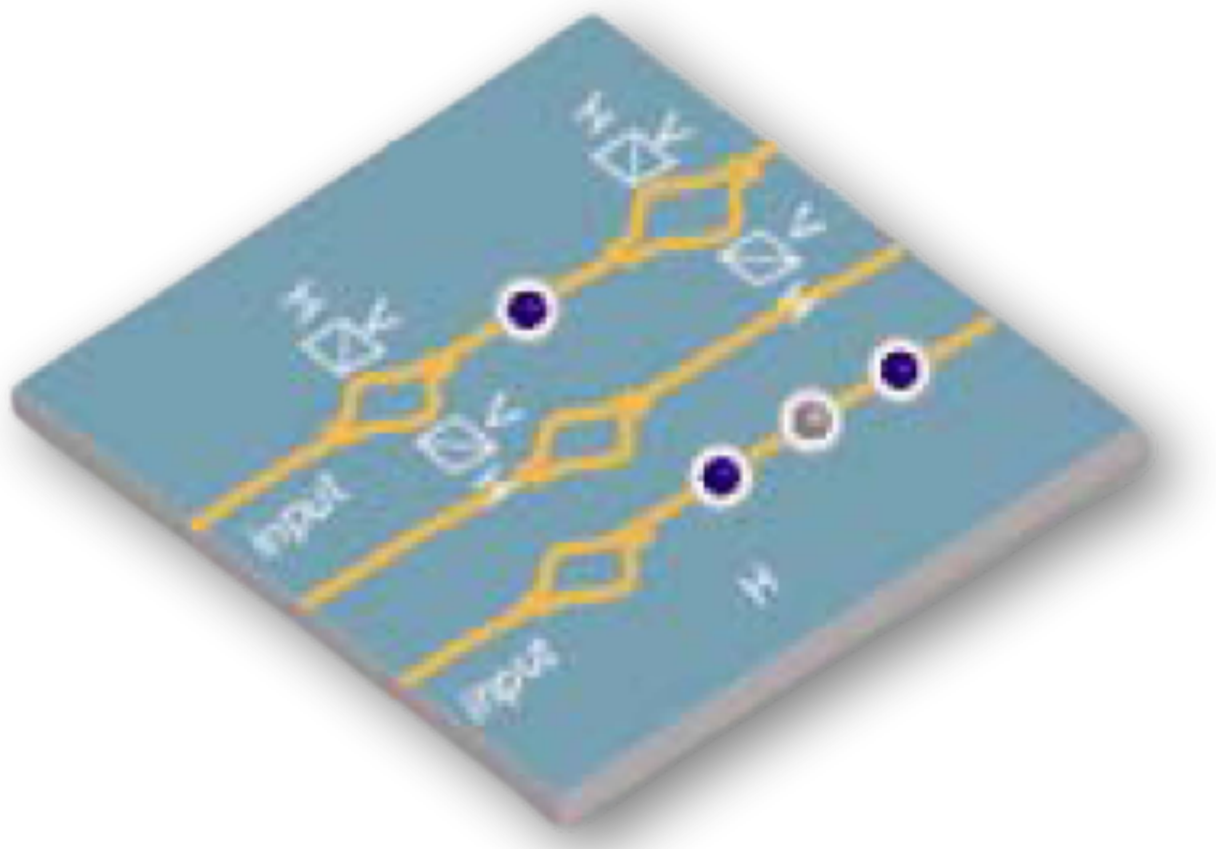
Atom-photon interface

1. Cold atoms in intersected waveguides





2. Scalable 2D architecture for photonic circuits

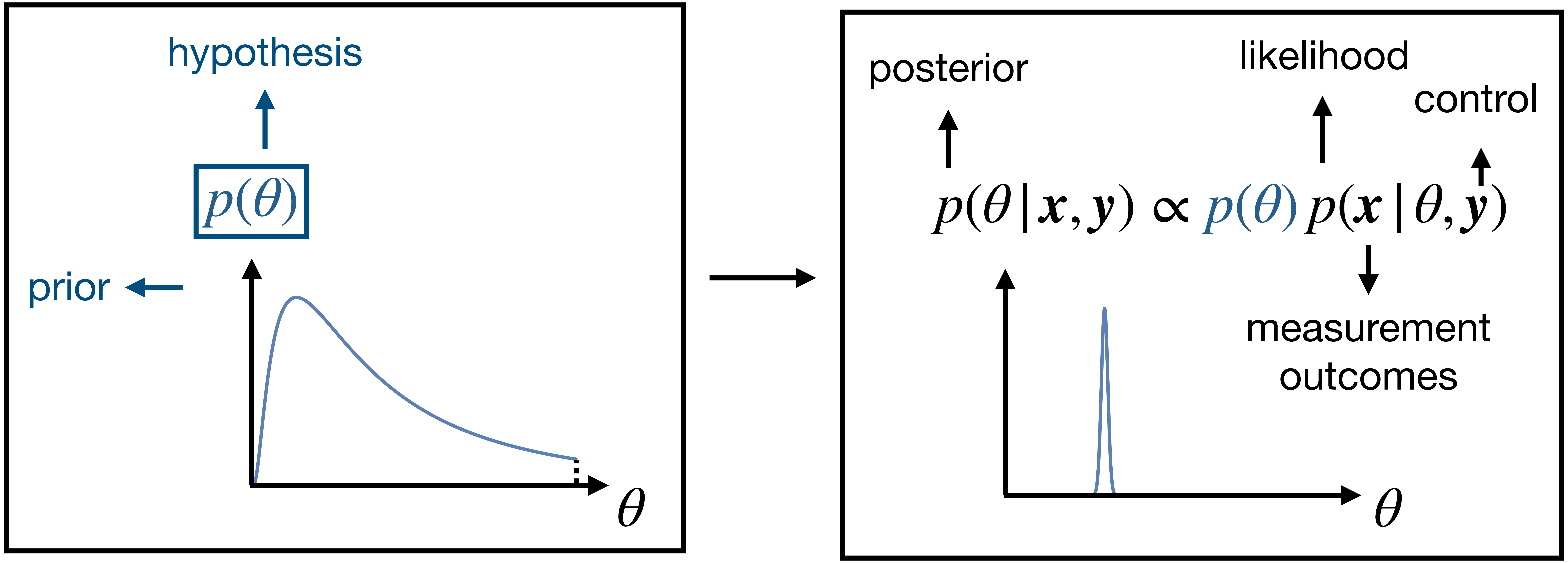


3. Applications

- Quantum memories
- Quantum networks
- Quantum sensors

E. Da Ros, PRR 2, 033098 (2020)

Bayesian inference for quantum technologies



Jaynes, Cambridge University Press (2003)

Optimal strategy: estimator, uncertainty, and gain

Estimator	$\tilde{\vartheta}_y(\boldsymbol{x}) = f^{-1}\left[\int d\theta\, p(\theta\,\vert\,\boldsymbol{x},\boldsymbol{y})\, f(\theta)\right]$
Empirical error	$\Delta\tilde{\vartheta}_y(\boldsymbol{x})^2 = \dfrac{\int d\theta\, p(\theta\,\vert\,\boldsymbol{x}, y)\, f(\theta)^2 - f[\tilde{\vartheta}_y(\boldsymbol{x})]^2}{f'[\tilde{\vartheta}_y(\boldsymbol{x})]^2}$
Precision gain	$\mathcal{G}_y = \int d\boldsymbol{x}\, p(\boldsymbol{x}\,\vert\,\boldsymbol{y})\, f[\tilde{\vartheta}_y(\boldsymbol{x})]^2$

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QST, 10, 045053 (2025)
PRA 110, L030401 (2024)

Symmetries select the optimal strategy

Parameter	location	scale	geometry
Symmetry	$\theta' = \theta + c$	$\theta' = \gamma\theta$	$f(\theta)' = f(\theta) + c$
Prior	$p(\theta) \propto 1$	$p(\theta) \propto \frac{1}{\theta}$	$p(\theta) \propto \sqrt{F(\theta)}$

Maximum ignorance compatible with the platform: $p_{\mathrm{MI}}(\theta)$

$$f(\theta) = \int^{\theta} dt\, p_{\mathrm{MI}}(t)$$

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QST, 10, 045053 (2025)
PRA 105, 042601 (2022)

Platform symmetries and location-isomorphic parameters

Step 1: calculate a relevant ignorance prior

	First constraint	Second constraint	
1	$n_\nu(\varphi', \theta') = n_\nu(\varphi, \theta)$	The laser frequency does not inform the unknown parameters	5
2	$\begin{cases} \zeta_\nu \theta' = \zeta_\nu \theta + \log(\gamma) \\ \varphi' = \gamma \varphi \end{cases}$	$p(\varphi, \theta \,\vert\, \nu) \mapsto p(\varphi, \theta)$	6
3	$p(\varphi', \theta' \,\vert\, \nu)\, d\varphi' d\theta' = p(\varphi, \theta \,\vert\, \nu)\, d\varphi d\theta$	$p(\varphi, \theta) \propto \frac{1}{\varphi}$	7
4	$p(\varphi, \theta \,\vert\, \nu) = \mathrm{e}^{-\zeta_\nu \theta} h(\varphi\, \mathrm{e}^{-\zeta_\nu \theta})$	$p(\varphi, \theta) = \left[(\theta_{\max} - \theta_{\min}) \log\left(\frac{\varphi_{\max}}{\varphi_{\min}} \right) \varphi \right]^{-1}$	8

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Step 2: marginalise over the nuisance parameter

$p(\theta) = \int d\varphi \, p(\varphi, \theta) \propto 1$	$p(\varphi) = \int d\theta \, p(\varphi, \theta) \propto \frac{1}{\varphi}$

Step 3: derive the symmetry function from the ignorance prior

$f(\theta) = \int^{\theta} dt \, p(t)$	$f(\theta) = \int^{\varphi} dt \, p(t)$
$f(\theta) = c_1 \theta + c_2$	$f(\varphi) = c_1 \log \left(\frac{\varphi}{c_2} \right)$

Symmetry-informed quantum sensing: core procedure

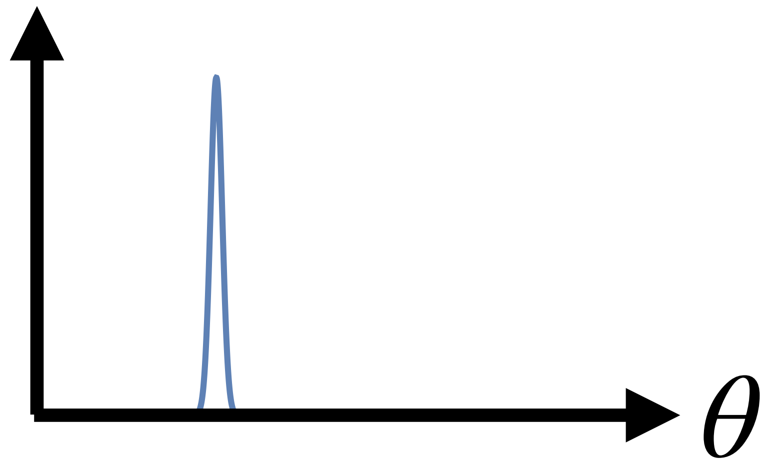
① **Statistical model** as proxy: *Poisson distribution with mean* $n_\nu(\varphi, \theta)$

②.a **Invariance:** $\begin{cases} \zeta_\nu \theta' = \zeta_\nu \theta + \log(\gamma) \\ \varphi' = \gamma \varphi \end{cases}$

②.b **Contextual information:** *the laser frequency carries no information about* φ, θ

③ Platform-dependent **ignorance prior:** ②.a + ②.b $\rightarrow$ $p_{\mathrm{MI}}(\varphi, \theta) \propto \dfrac{1}{\varphi}$

④ **Optimal strategy:** ① + ③ $\rightarrow$ $\tilde{N}_\nu(\boldsymbol{x}) \pm \Delta \tilde{N}_\nu(\boldsymbol{x})$ are the mean and std. dev. of



$$p(\theta \,|\, \boldsymbol{x}, \boldsymbol{\nu}) \propto \int_{\varphi_{\min}}^{\varphi_{\max}} \frac{d\varphi}{\varphi} \prod_{i=1}^{k} p(x_i \mid \varphi, \theta, \nu_i)$$

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Symmetry-informed quantum sensing: core procedure

1. **Statistical model** as proxy: *Poisson distribution with mean* $n_\nu(\varphi, \theta)$

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2.b **Contextual information:** *the laser frequency carries no information about* φ, θ

3. Platform-dependent **ignorance prior:** 2.a + 2.b $\rightarrow$ $p_{\mathrm{MI}}(\varphi, \theta) \propto \dfrac{1}{\varphi}$

4. **Precision gain to be maximised** within the adaptive loop:

$$\mathcal{G}_\nu \propto \int d\boldsymbol{x}\, p(\boldsymbol{x} \,|\, \nu)\, \tilde{N}_\nu(\boldsymbol{x})^2$$

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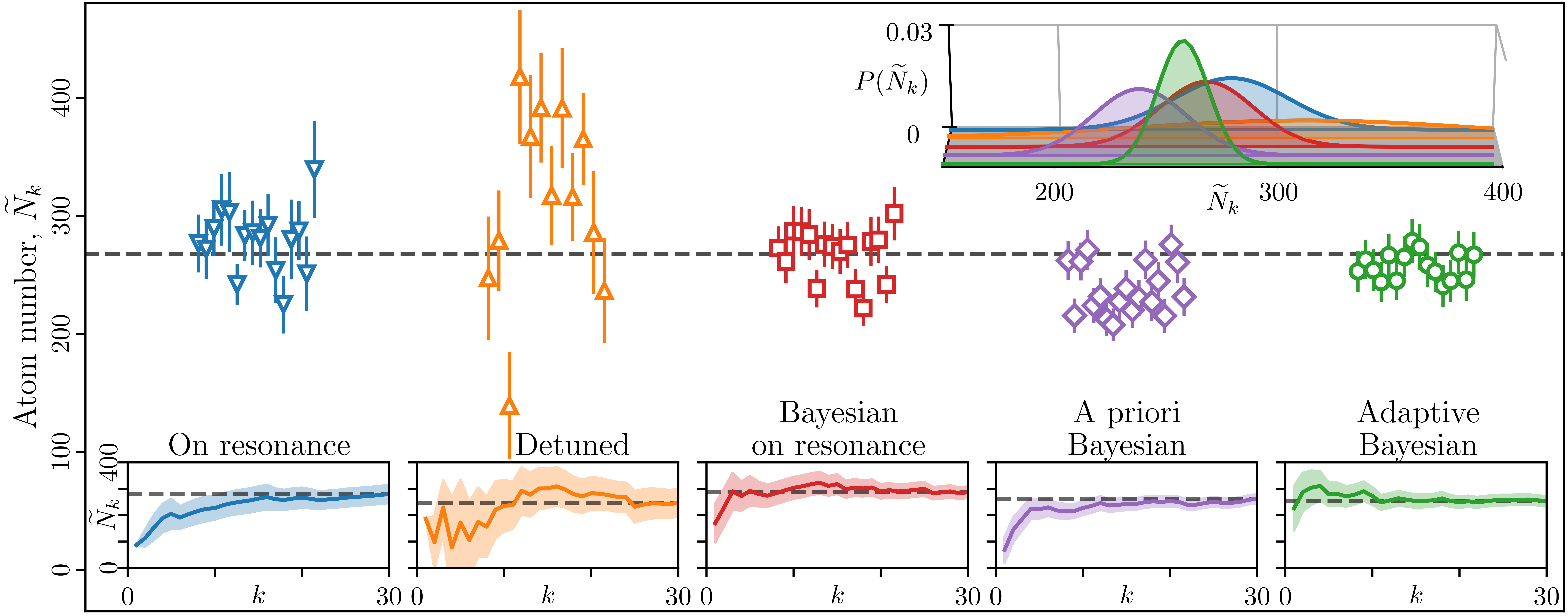
Bayesian methods outperform local estimation



- Target atom number: ~280
- 30 independent repetitions per method

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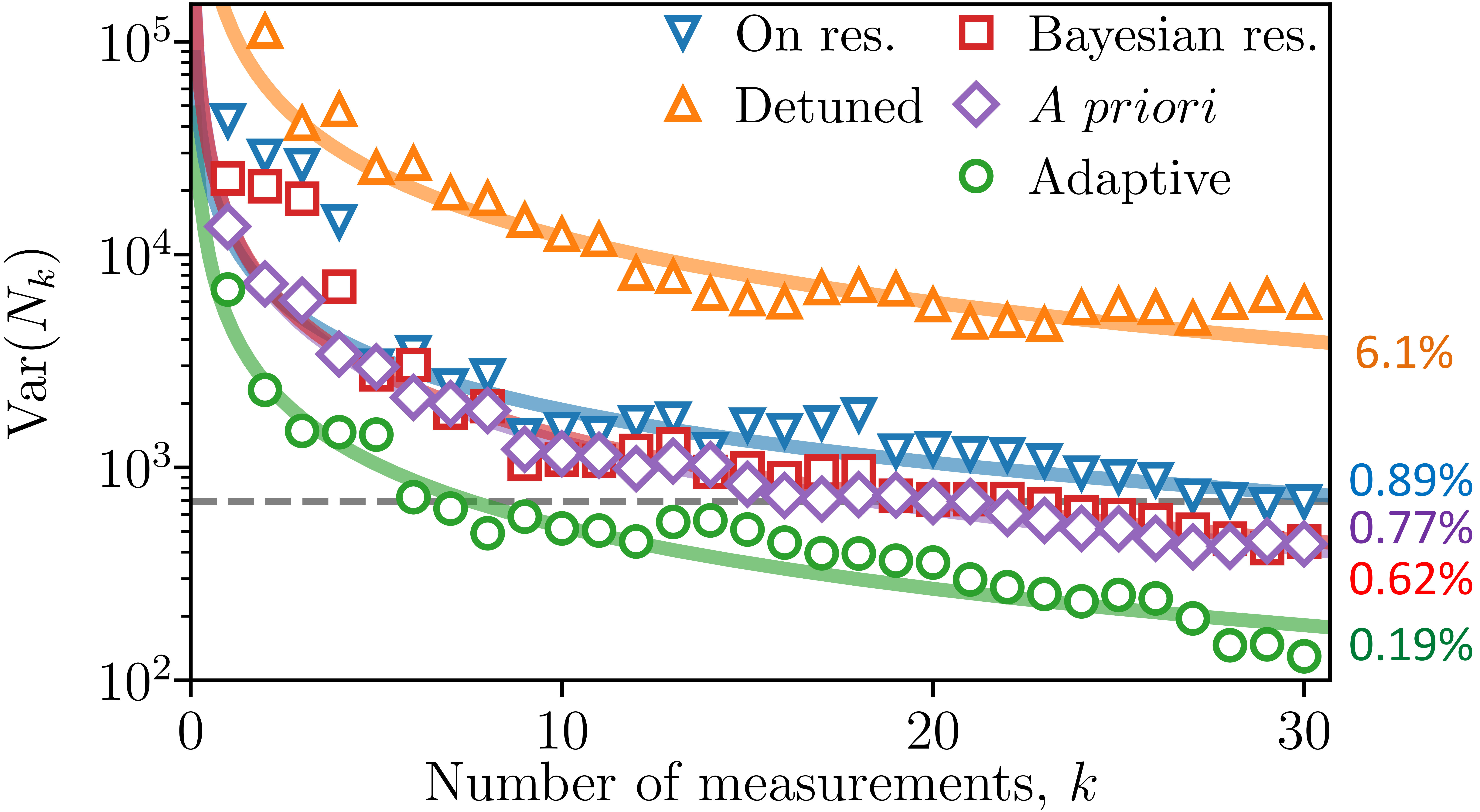

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Bayesian multiparameter quantum estimation

Symmetry posterior mean (SPM) bound	$\mathscr{L} \geq \mathscr{L}_{\text{SPM}} = \text{Tr}\left\{ L \left[\int d\boldsymbol{\theta}\, p(\boldsymbol{\theta})\, \boldsymbol{\theta}\boldsymbol{\theta}^T - \text{Tr}\left(\rho_{\boldsymbol{y},0}\, \boldsymbol{\mathcal{S}}_{\boldsymbol{y}} \boldsymbol{\mathcal{S}}_{\boldsymbol{y}}{}^T \right) \right] \right\}$
Measurement incompatibility	$2\mathscr{L}_{\text{SPM}} \geq \mathscr{L}_{\min} \geq \mathscr{L}_{\text{SPM}}$

- Measurement incompatibility is bounded by **a factor of two**
- Classical problem: solved analytically
- Quantum problem: currently solved numerically

arXiv:2511.16645

Symmetry-informed quantum estimation

Theory contributions

- arXiv:2511.16645
- Quantum Sci. Technol., 10, 045053 (2025)
- Phys. Rev. A, 110, L030401 (2024)
- Quantum Sci. Technol., 8, 015009 (2023)
- Phys. Rev. Lett., 127, 190402 (2021)

Experimental contributions

- Phys. Rev. Lett. 136, 140801 (2026)
- J. Chem. Theory Comput., 20, 1, 385-395 (2023)
- PRX Quantum 3, 040330 (2022)

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