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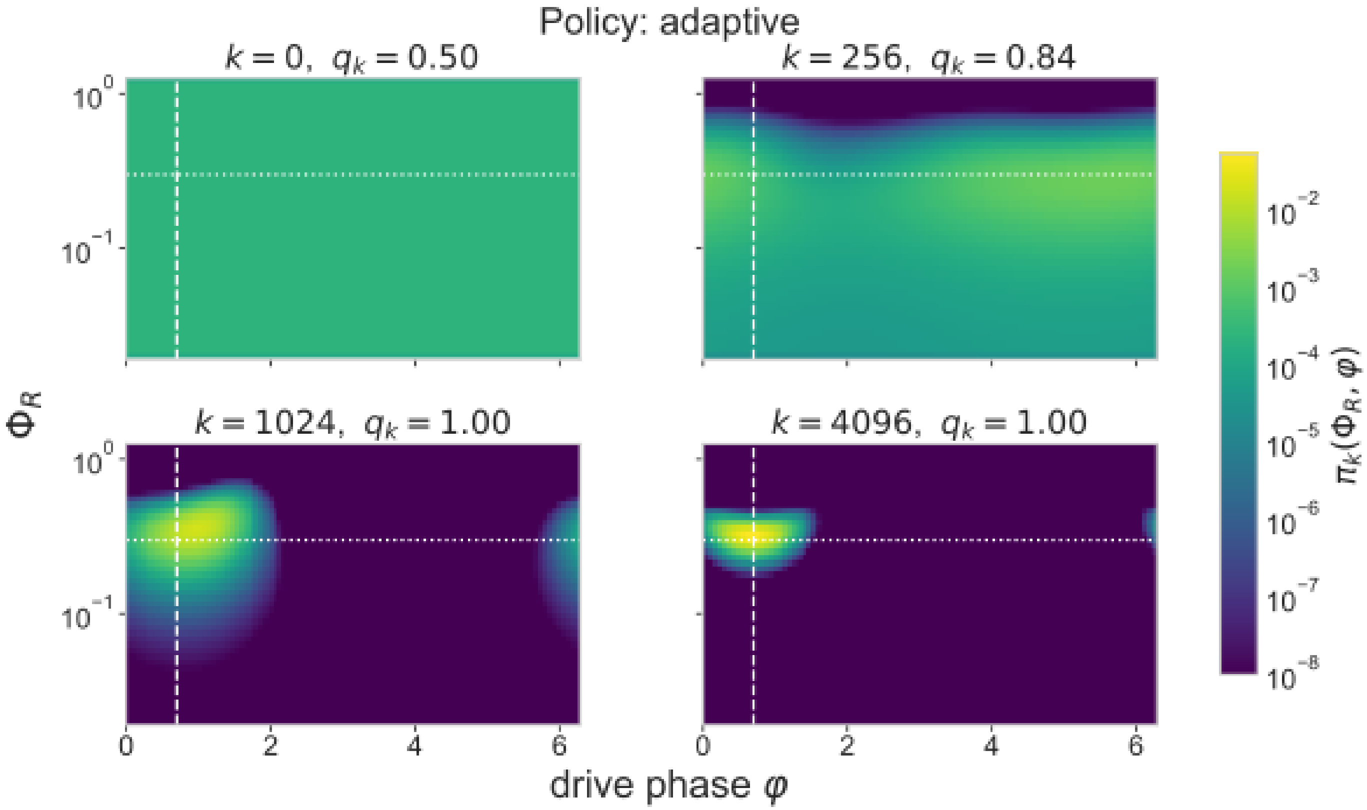
C²QA



Adaptive quantum sensing
for wave-like dark matter searches

arXiv: [2608.xxxxx]
In collaboration with Codex

So Chigusa (Postdoctoral Fellow)

Light Dark World 2026 @ Carleton (7/28/2026)

Wave dark matter signals at direct detection

❖ Coherent oscillation of classical wave dark matter (DM)

$$a(t) = a_0 \sin(m_{\mathrm{DM}} t - m_{\mathrm{DM}} \vec{v}_{\mathrm{DM}} \cdot \vec{x} + \delta)$$

❖ Unknown properties of DM signals

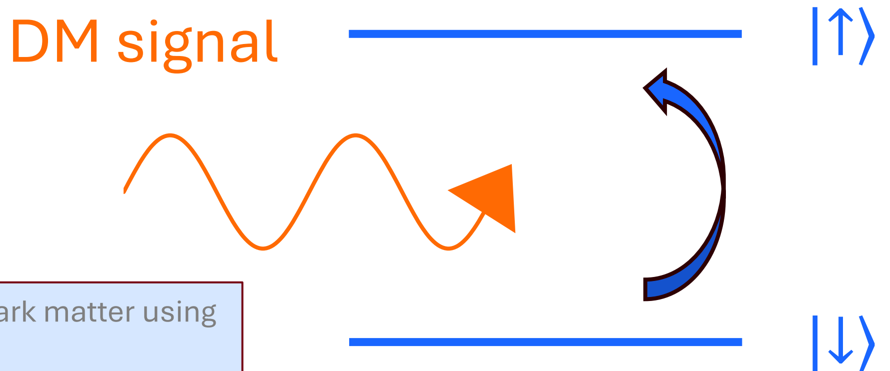
- Frequency $= m_{\mathrm{DM}}$
- Amplitude $\propto a_0$
- Oscillation phase $= \delta$
- Direction

  ex) Dark photon polarization

  Axion-induced $\vec{B}_{\mathrm{eff}}$

❖ Resonant drive

as example of quantum sensing



$m_{\mathrm{DM}} \simeq \omega_{\mathrm{qubit}}$

Example: "Detection of hidden photon dark matter using the direct excitation of transmon qubits" [Chen, et al. PRL '23]

Classical interpretation and projective measurements

❖ Classical interpretation

- "DM signal flips the qubit spin at probability p"

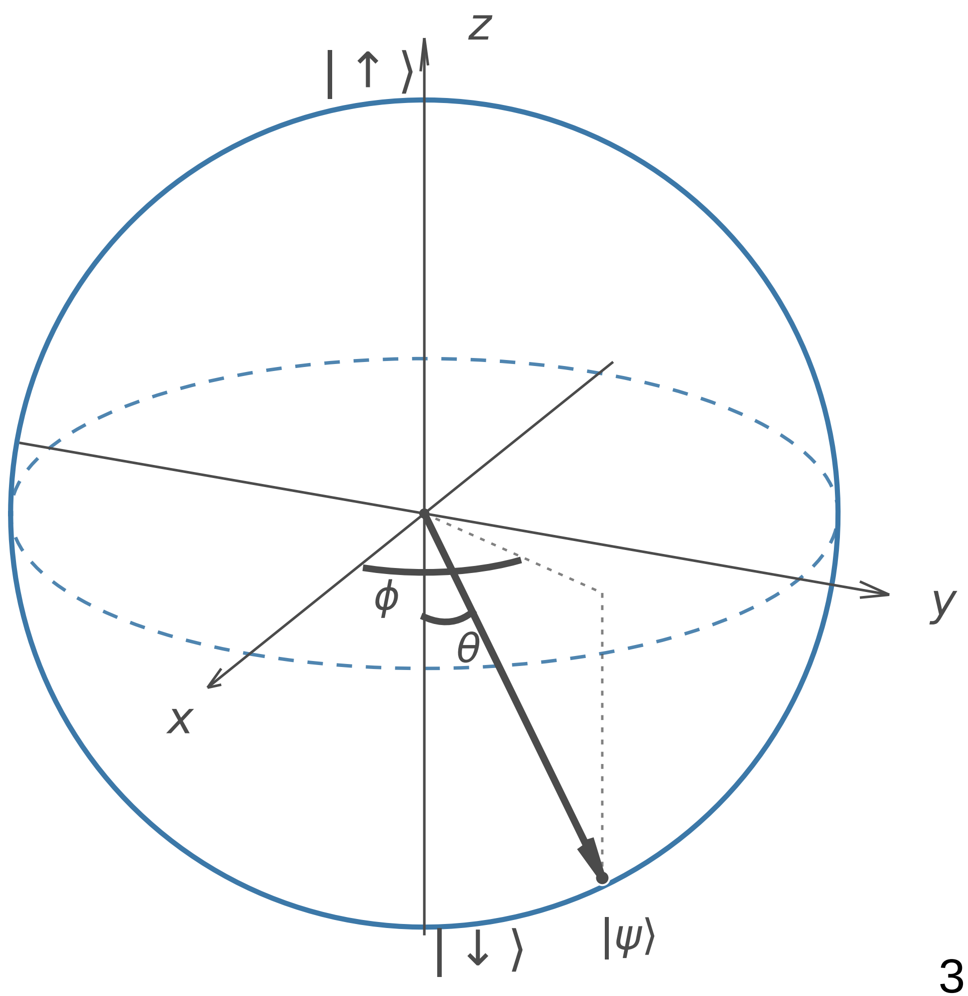
❖ Quantum description

$$|\psi\rangle = \cos\frac{\theta}{2}|\downarrow\rangle + \sin\frac{\theta}{2}e^{i\phi}|\uparrow\rangle$$

- $p = \sin^2\frac{\theta}{2}$
- Additional information from ϕ

❖ Projective measurement

- DOF of readout-axis choice
- "Classical" $=$ z-projective measurement



Longitudinal vs transverse readout

❖ z-readout

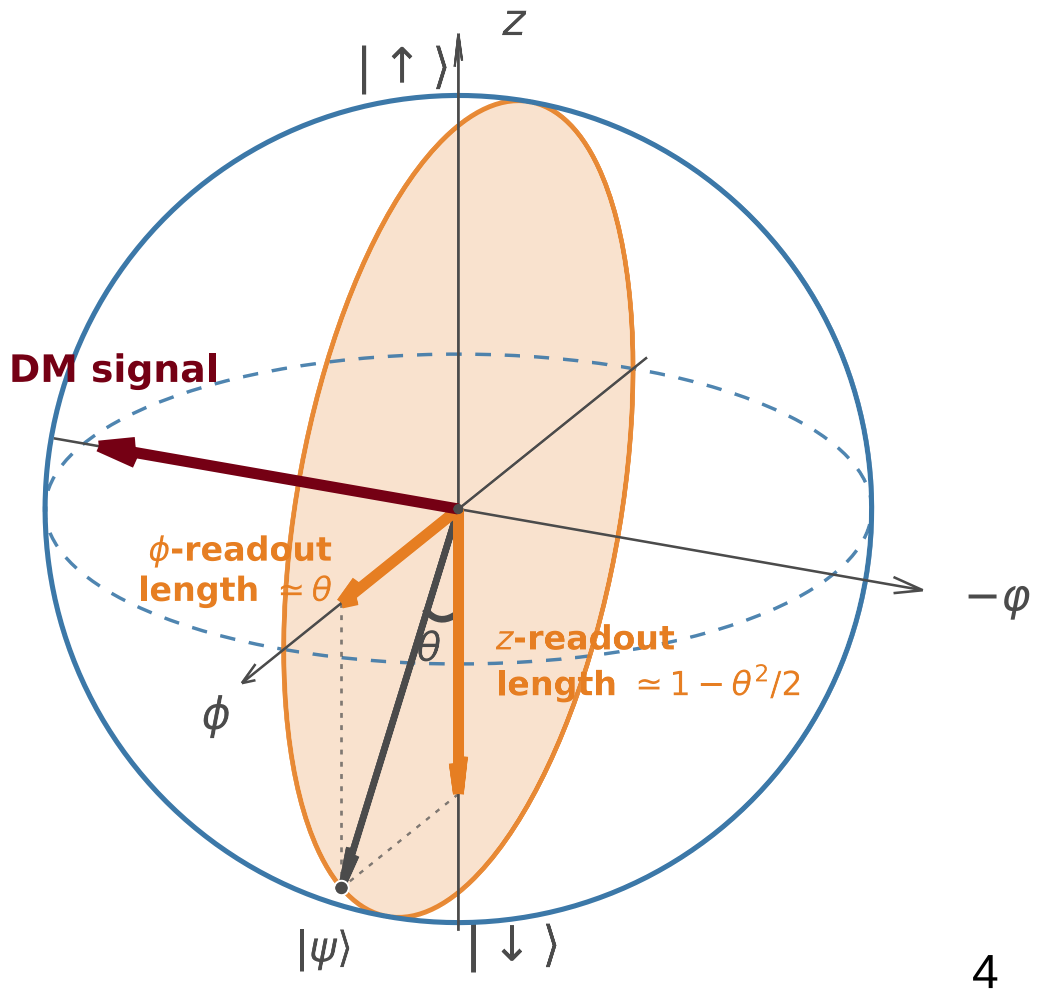
- Insensitive to unknown phase ϕ
- Quadratic response $2\sin^2(\theta/2) \propto \theta^2$

❖ Transverse oracle ϕ-readout

- Linear response $\propto \theta$
- Need to know ϕ

❖ ϕ is determined by signal direction

- For $\vec{E}_{\mathrm{sig}} = \cos\varphi\,\hat{x} + \sin\varphi\,\hat{y}$
- $\phi = \varphi + \pi/2$ is unknown $\Longrightarrow$ learn it!



Adaptive strategy

❖ During repeated measurements with $n_{\rm shots}$ total shots,

Start with z-readout

- Phase-insensitive signal search

Phase learning

- Insert trial shots (information gain) to learn the signal phase φ

Converge to transverse oracle

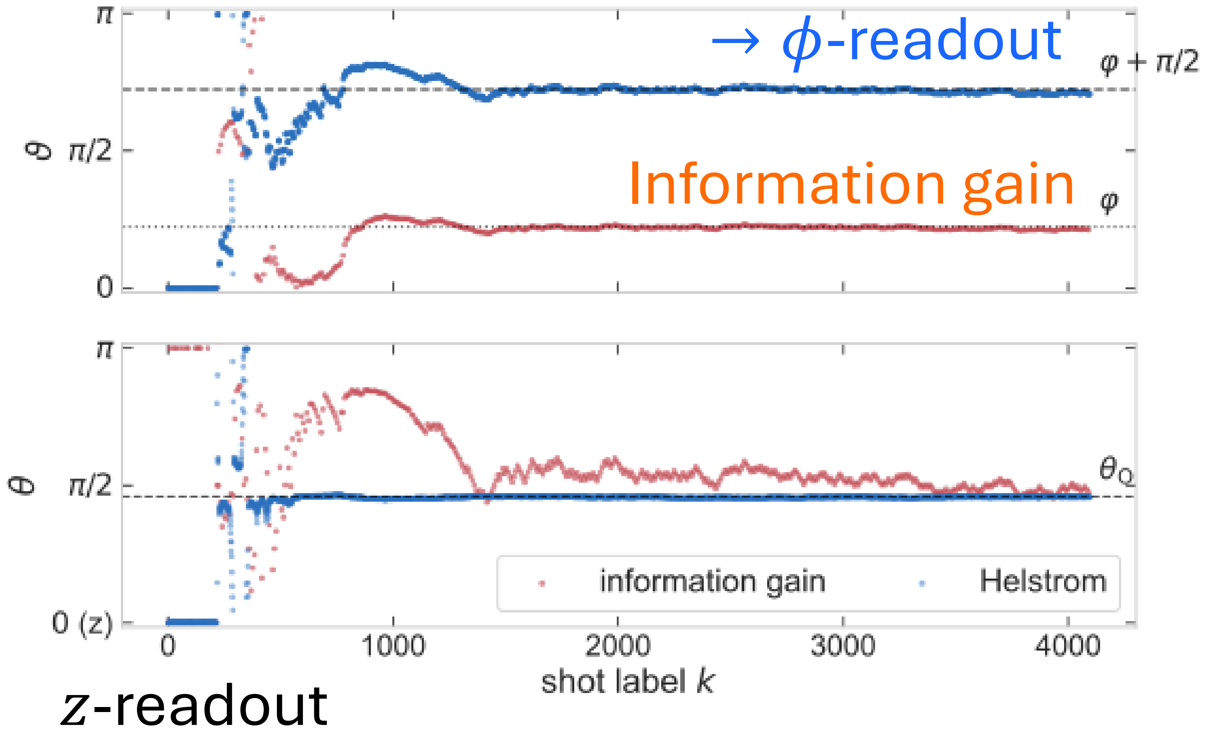
- The optimal ϕ-readout for signal detection

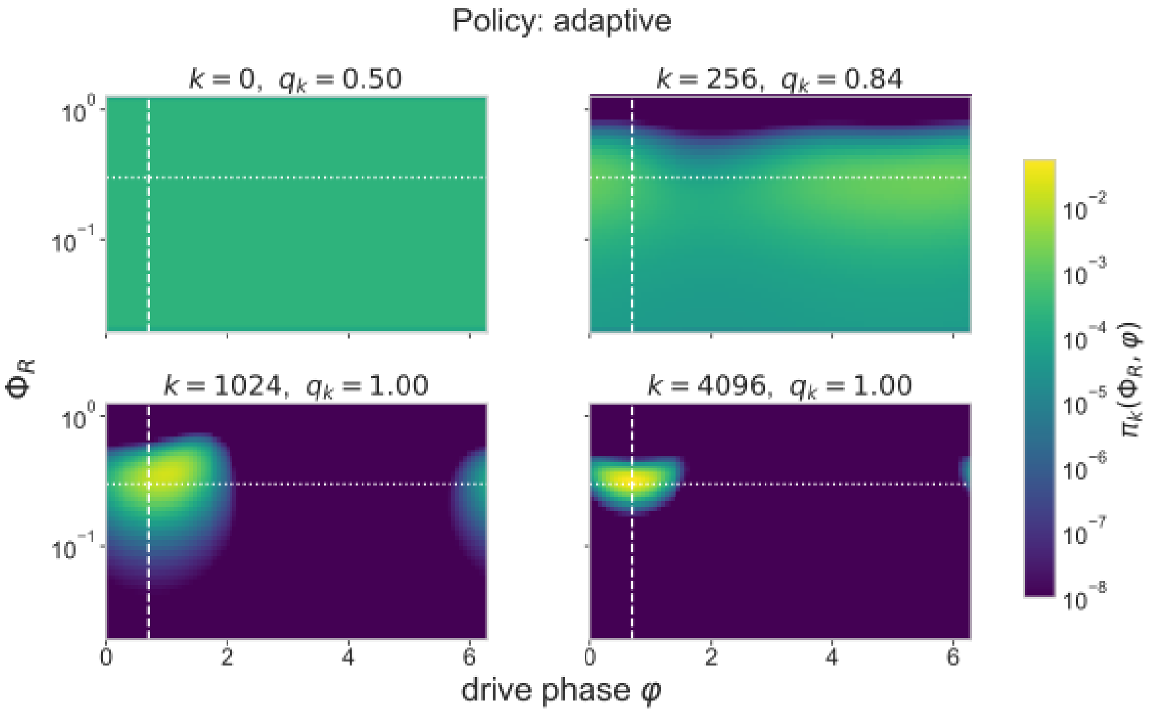
❖ Resilient to fake positives/look-elsewhere effects

Adaptive trajectory

❖ Noisy environment simulation: Relaxation (T_1, T_2), Readout contrast & error

❖ Bayesian analysis tracking prior/posterior distribution of nuisance parameters





Sensitivities

❖ Statistical formulation

- Composite hypothesis test

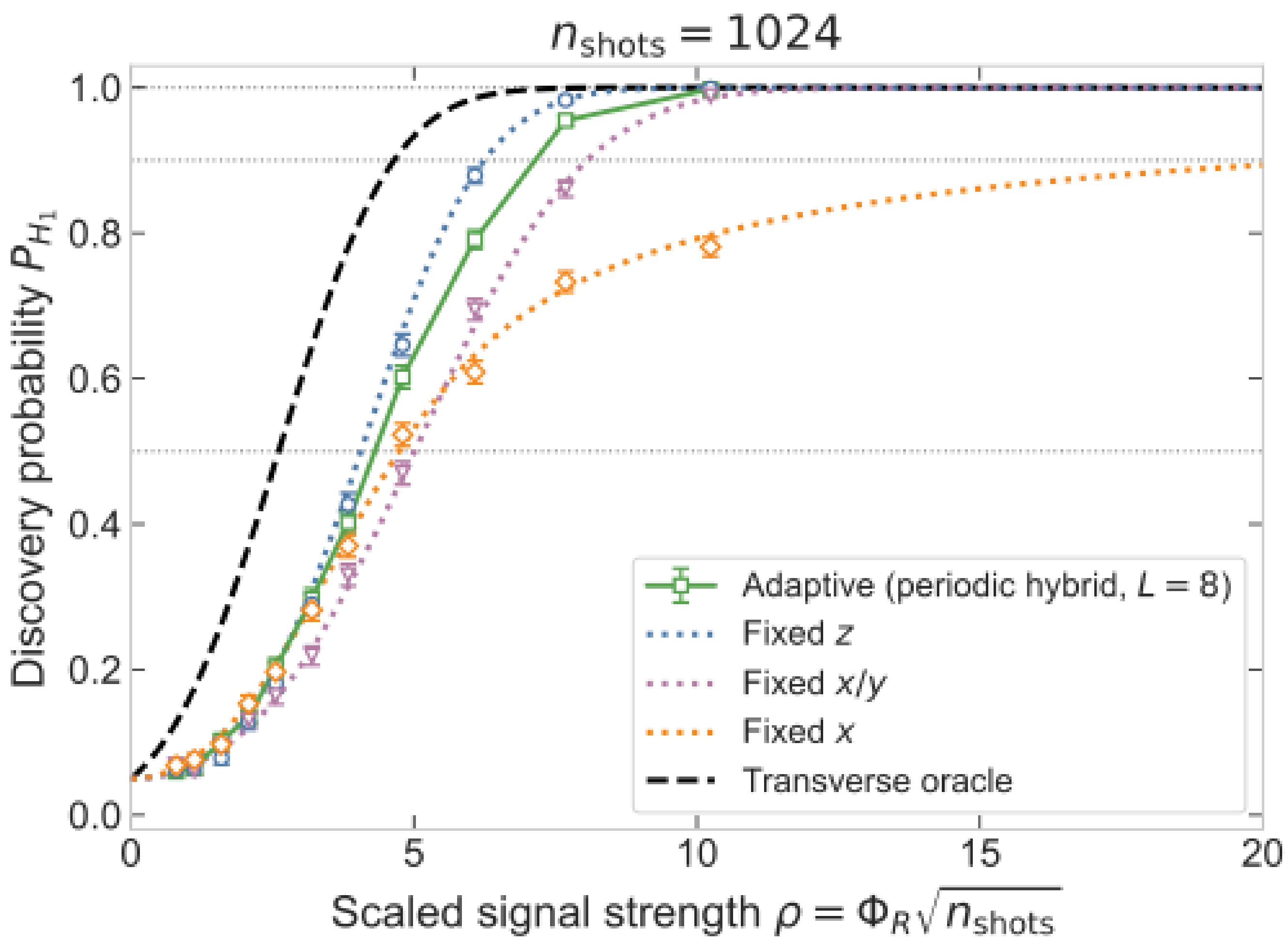
 Noise only vs  Noise+DM

- Asymmetric testing

Keep false-positive rate $< 5\ \%$

❖ Best strategy for increasing n_{shots}

1. z-readout for small n_{shots}
2. Adaptive for large n_{shots}



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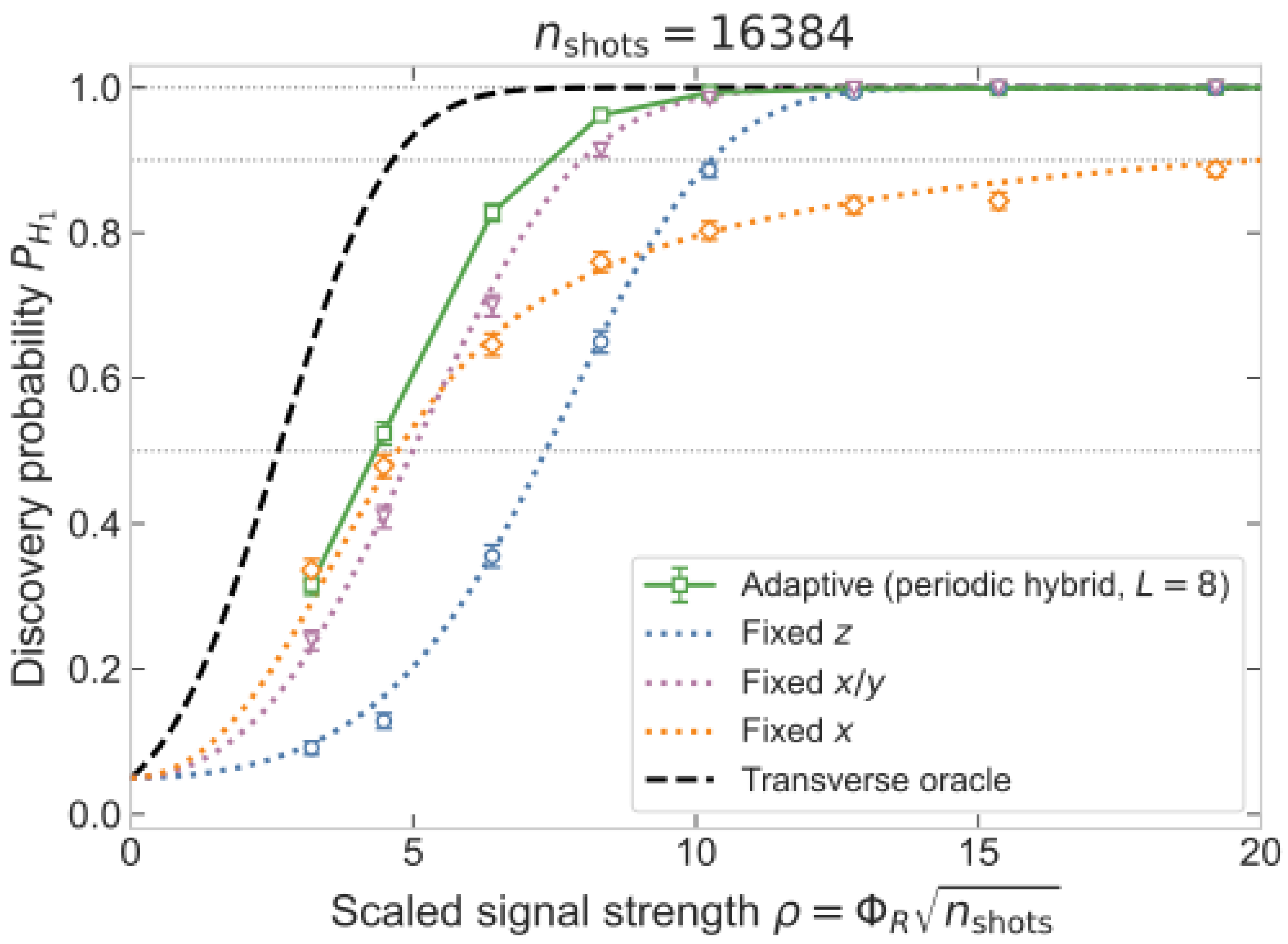


Sensitivity scaling and comparison

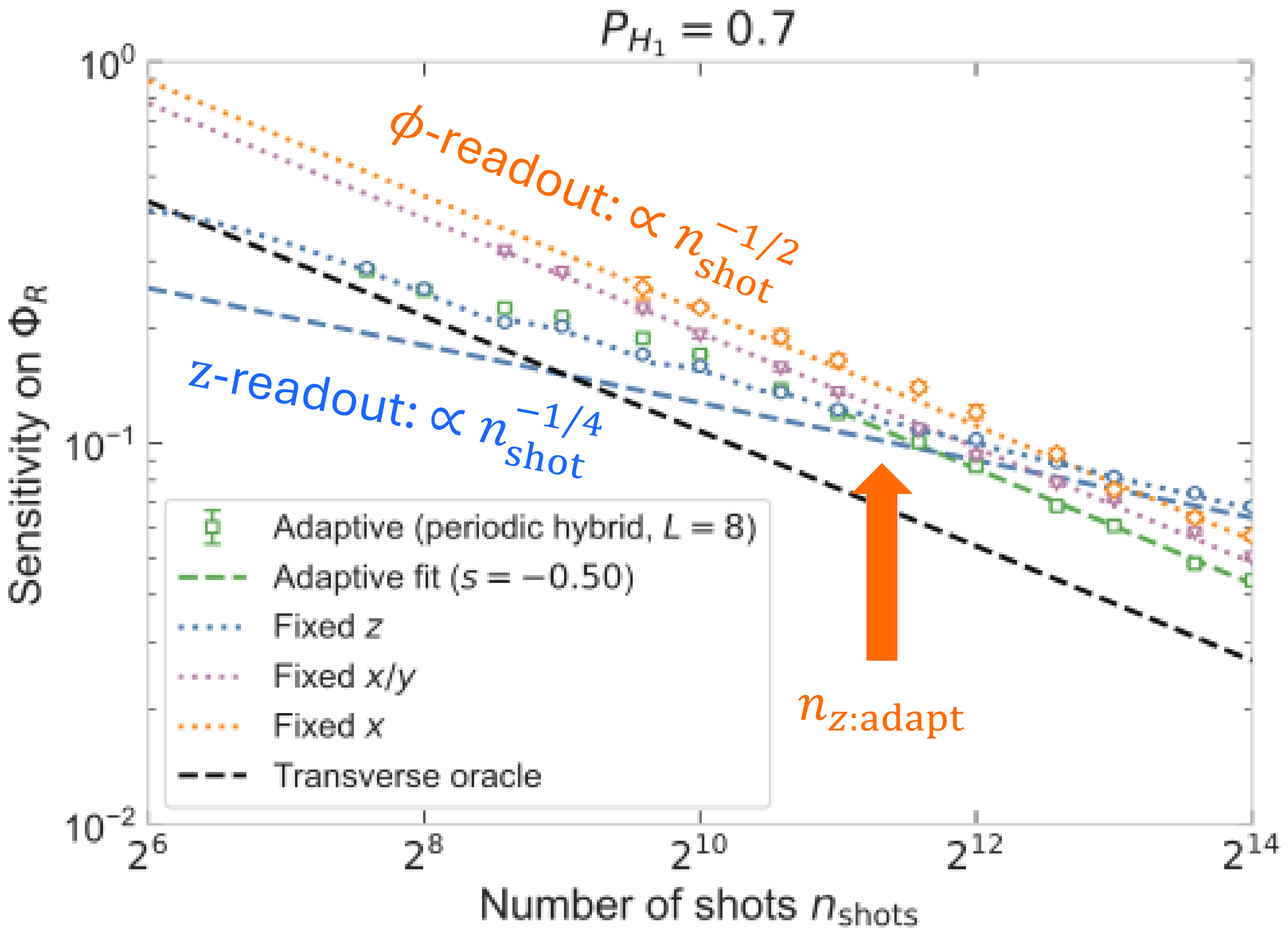
❖ Crossings due to different scaling

P_{H_1}	$n_{z:O_\perp}$	$n_{z:\mathrm{adapt}}$	$n_{z:xy}$	$n_{z:x}$
0.50	2.97×10^2	1.53×10^3	3.99×10^3	3.20×10^3
0.70	5.17×10^2	1.99×10^3	5.54×10^3	9.50×10^3
0.90	9.41×10^2	3.12×10^3	8.22×10^3	3.21×10^5
0.95	1.19×10^3	3.51×10^3	9.69×10^3	3.97×10^6

❖ Phase information efficiency

- $f_{\mathrm{pol}} \equiv 2\left\langle \left\{\hat{n}_{\mathrm{sig}} \cdot (\hat{n}_{\mathrm{meas}} \times \hat{z})\right\}^2 \right\rangle$

$$= \begin{cases} 1 & \text{(fixed x/y)} \\ 1.15 - 1.32 & \text{(adaptive)} \\ 2 & \text{(oracle)} \end{cases}$$



Takeaways and discussions

❖ Implication to decision making

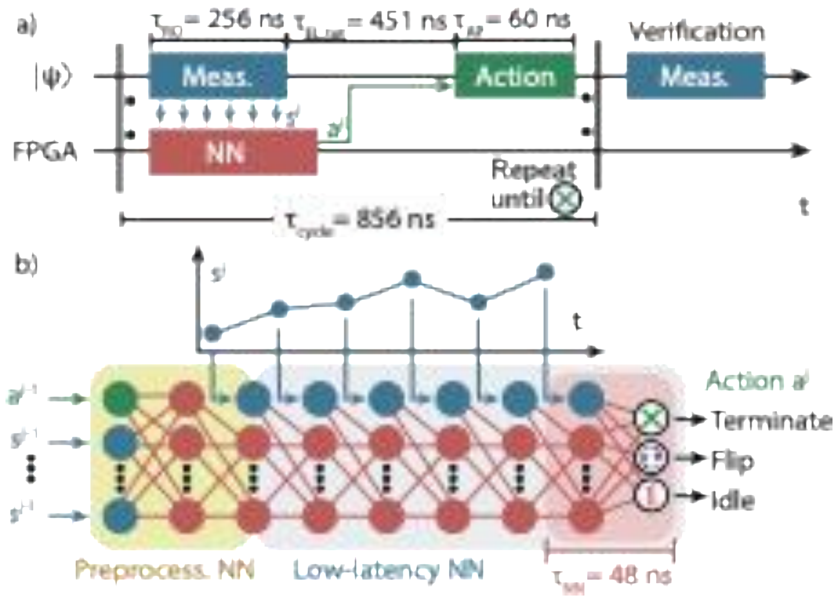
- Adaptive is best for $n_{\mathrm{shots}} \gtrsim n_{z:\mathrm{adapt}}$
- $n_{z:\mathrm{adapt}}$ is independent of DM properties

❖ Online update, NOT offline analysis

- Info discarded by measurement never recovered

❖ Prospects

- Global optimization ⟹ DRL
- Optimize initial state, interrogation time, etc. ⟹ VQA



"Realizing a deep reinforcement learning agent discovering real-time feedback control strategies for a quantum system"
[Reuer, et al. Nat. Comm. '23]

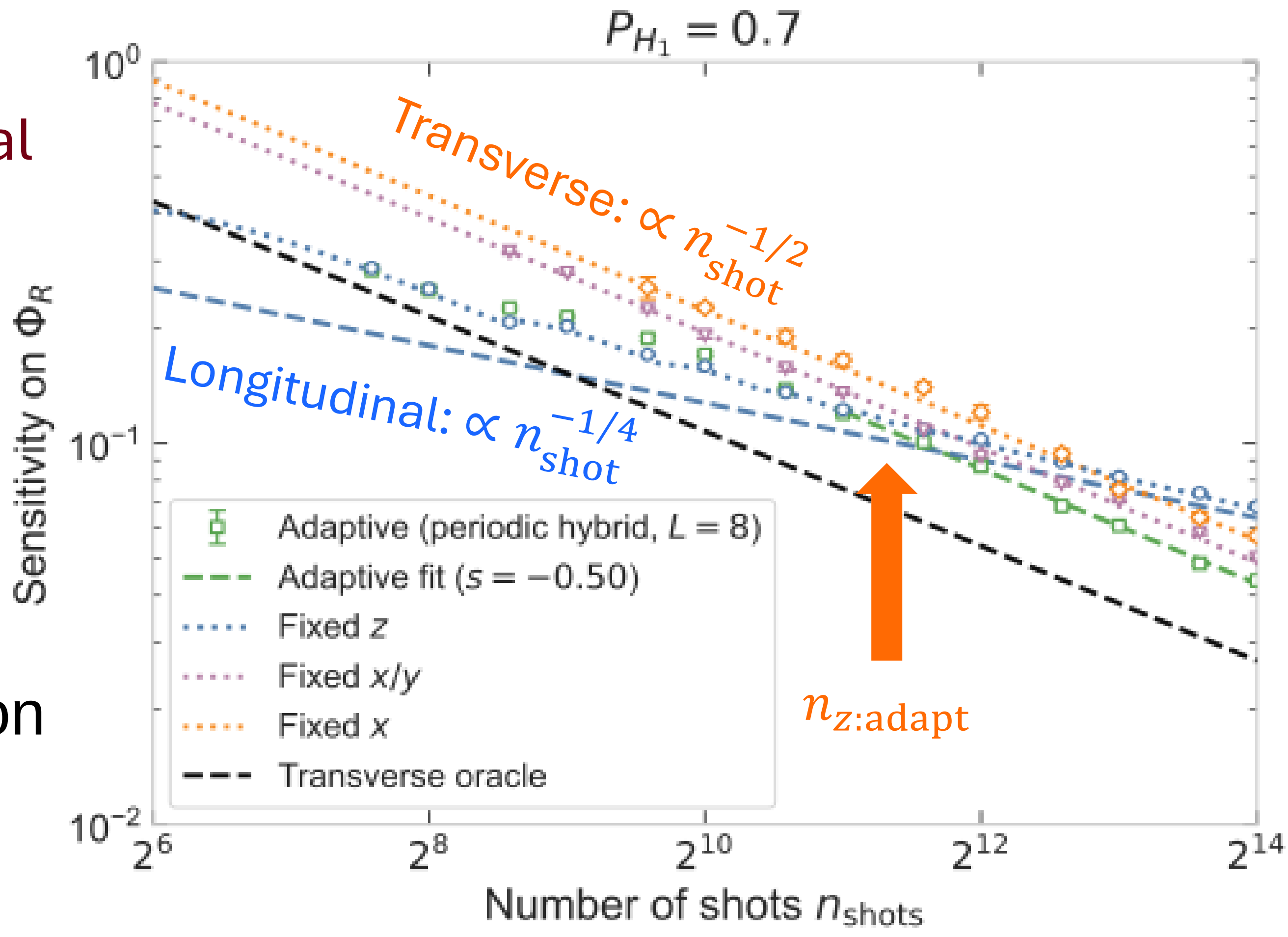
Conclusion

❖ Main message

- Adaptive strategy can be beneficial for DM searches
- The best search strategy determined solely by detector setups; deserves a consideration during experimental design

❖ Fascinating interdisciplinary direction

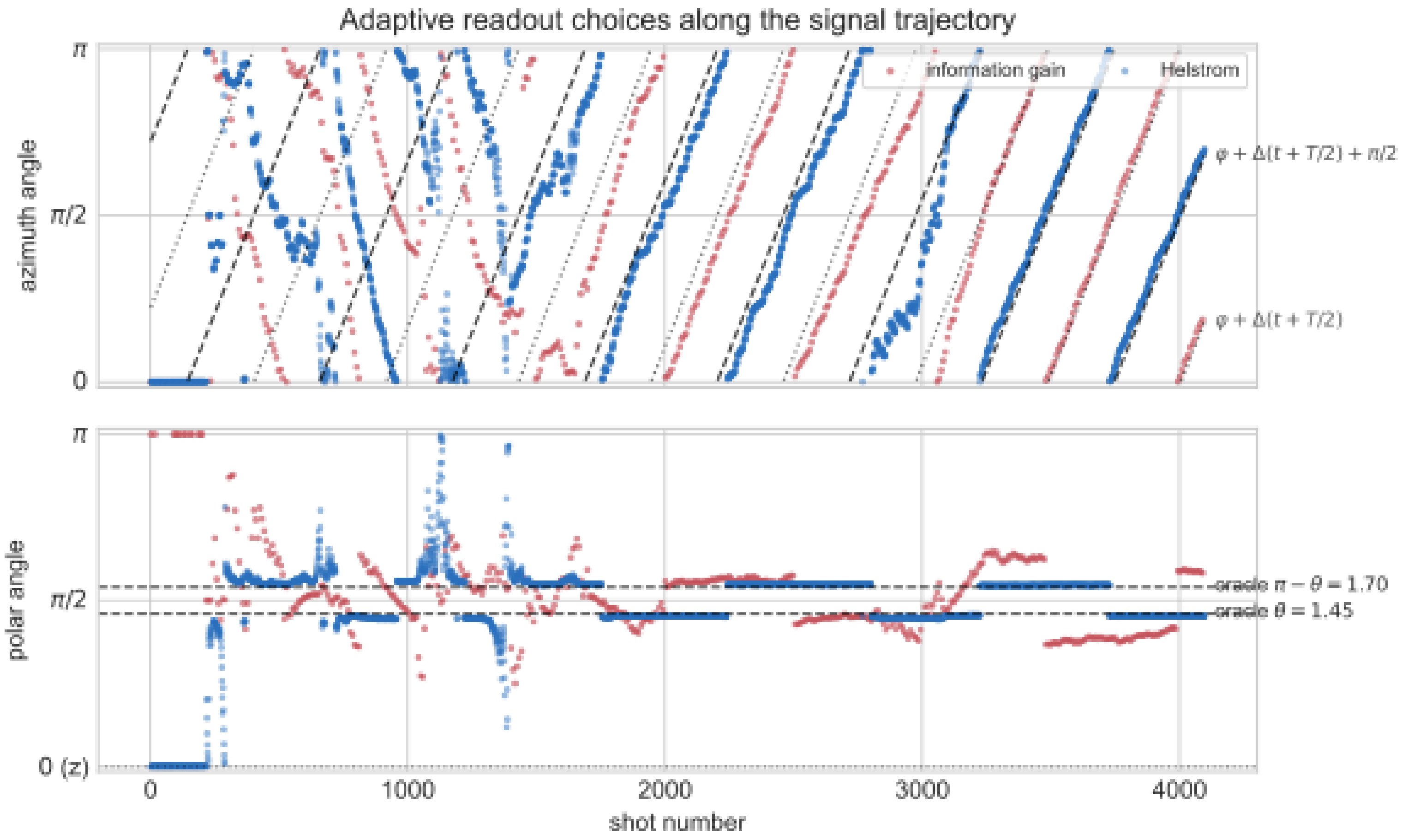
Particle × Quantum × ML



Backup slides

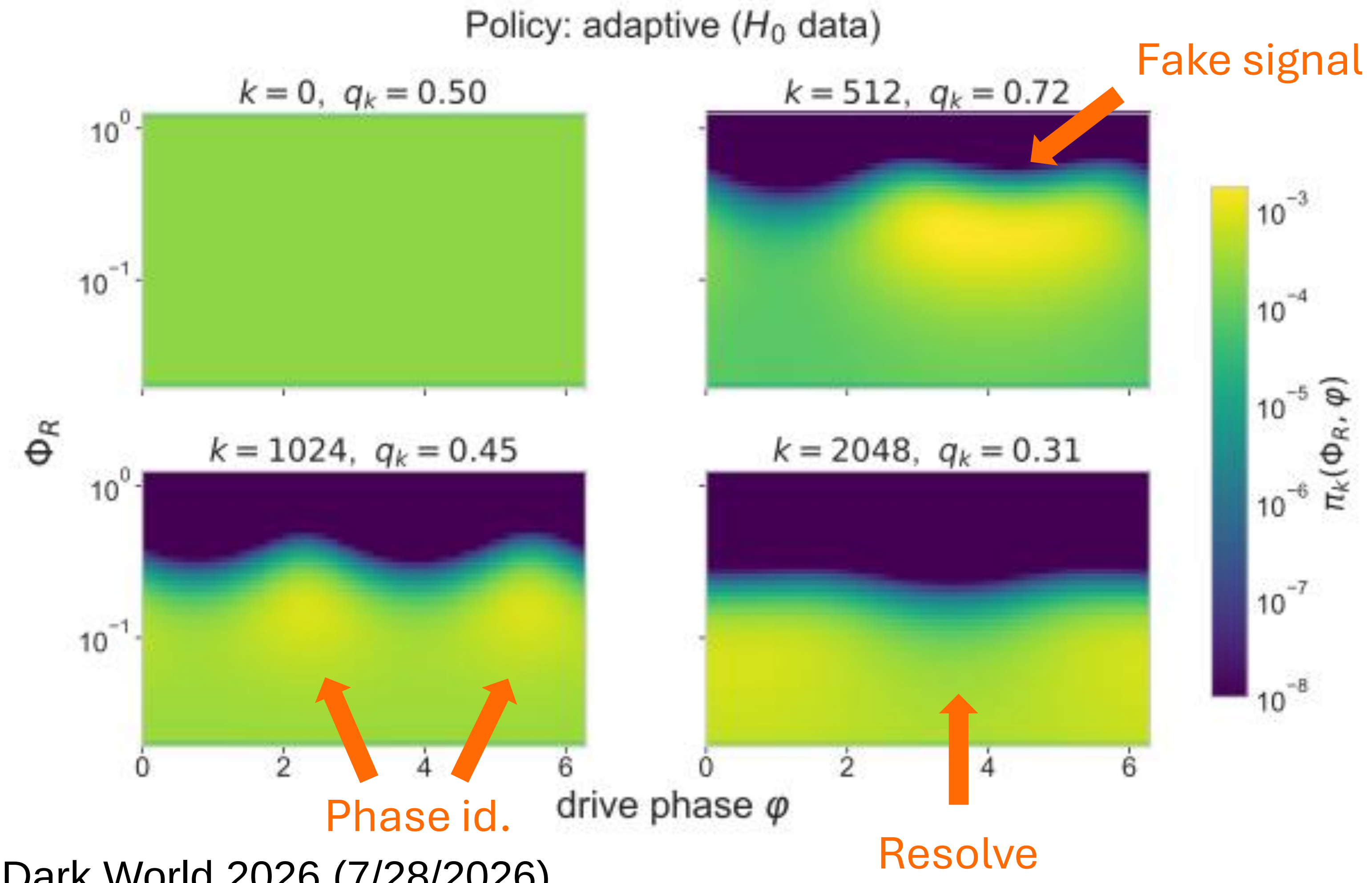
Detuning effects

❖ Detuning Δ makes optimal readout time-dependent: $\phi(\mathrm{t}) = \varphi + \pi/2 + \Delta\,\mathrm{t}$



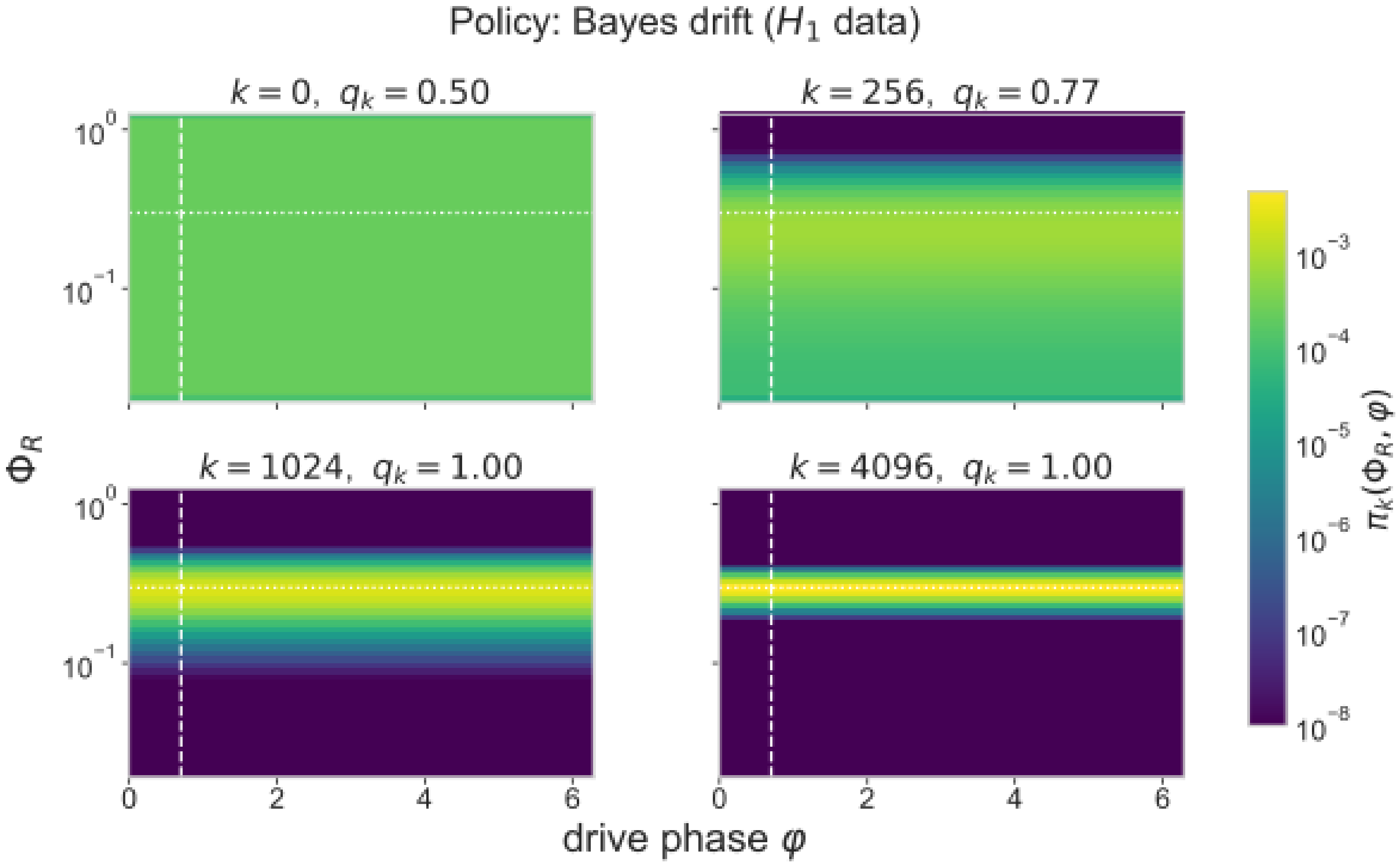
Visualizing look-elsewhere effects

❖ No signal simulation



Repeated local optimization ≠ global optimization

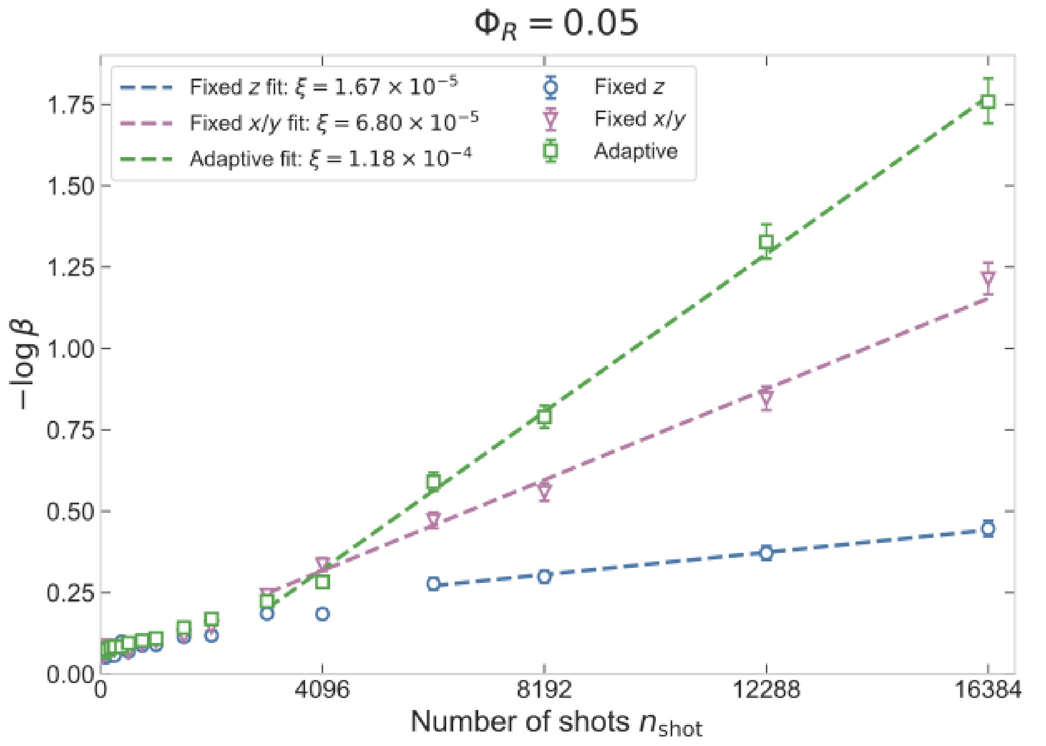
❖ Fixed-z is the best with unknown phase ⟺ No phase information is learned



Information theory for hypothesis test

❖ Type-II error (false negative) rate decays exponentially

- $\beta \to \exp[-n\xi + o(n)]$
- $\xi = D_{\mathrm{KL}}(P_0||P_1)$: Kullback–Leibler divergence



❖ Relevant QI quantity: relative entropy $D(\rho_0||\rho_1)$

- Max extractable information: $D_{\mathrm{KL}} \leq D$

  cf: Fisher information for measurement

  cf: Chernoff bound for symmetric testing

Assumed experimental setups

❖ Detector performance (optimistic transmon qubit)

- $T_1 = T_2 = T$: interrogation time
- Measurement contrast $C = 0.999$
- Readout error rate $\epsilon = 0.05\ \%$

P_{H_1}	$n_{z:\mathrm{O}_\perp}$	$n_{z:\mathrm{adapt}}$	$n_{z:xy}$	$n_{z:x}$
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❖ For false-positive rate $\alpha = 5\ \%$ and detection power $\mathrm{P} = 1 - \beta = 95\ \%$

$$n_{z:\mathrm{adapt}} \simeq \frac{19.2749}{f_{\mathrm{pol}}^2\left((1-C)+2\epsilon\right)}\left[1 + O(1-C,\epsilon)\right]$$