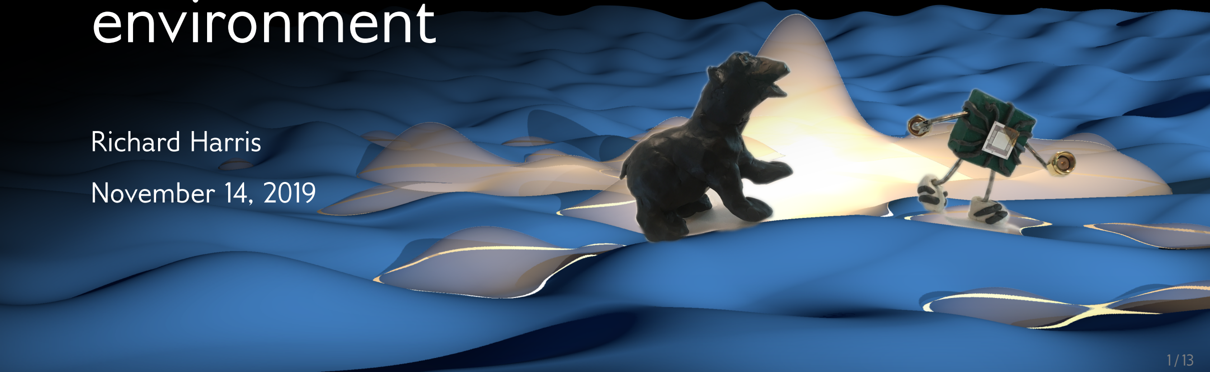
D:WAVE
The Quantum Computing Company™

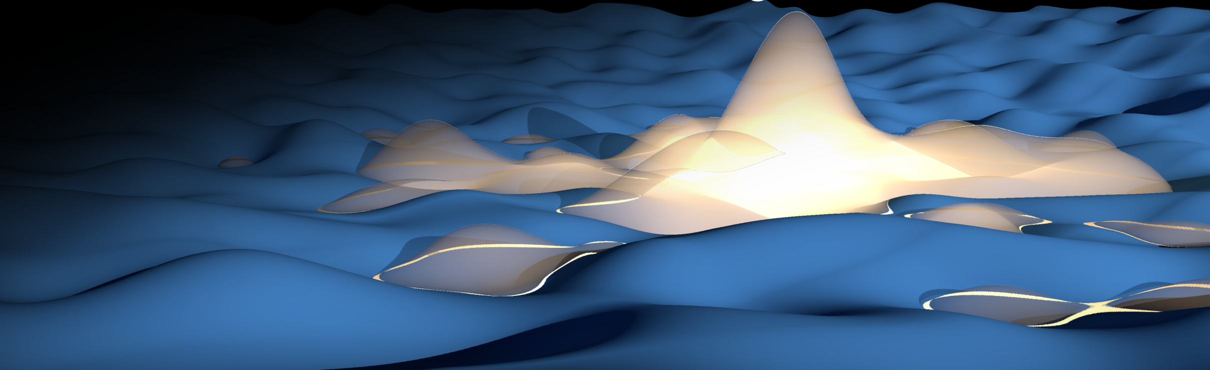
Outrunning the bear: QA in the presence of an environment



Richard Harris

November 14, 2019

Quantum annealing (QA)



Quantum annealing (QA)

A heuristic method that harnesses phase transitions in quantum spin systems: $S_i \to \sigma_i^z$ and introduce quantum fluctuations via σ_i^x.

$$\mathcal{H}_{\mathrm{QA}}(t) = [1 - s(t)]\,\mathcal{H}_i + s(t)\mathcal{H}_f$$

$$0 \leq s(t) \leq 1$$

$$\mathcal{H}_i = -\sum_i \sigma_x^{(i)} \qquad \mathcal{H}_f = \sum_i h_i \sigma_z^{(i)} + \sum_{<ij>} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)}$$

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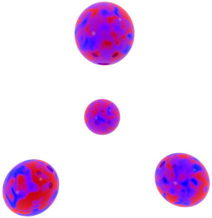
🔵 $\equiv$ ‘up’ or $+1$

🔴 $\equiv$ ‘down’ or -1

$s_c \equiv$ critical point

$s(t) = 0$



product state

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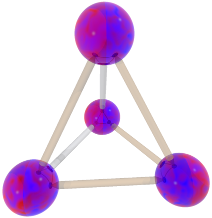
$0 < s(t) < s_c$



weakly entangled state

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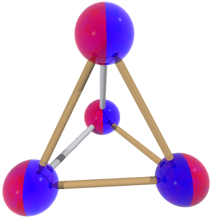
$s(t) \lesssim s_c$



strongly entangled state

Quantum annealing (QA)

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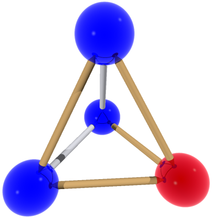
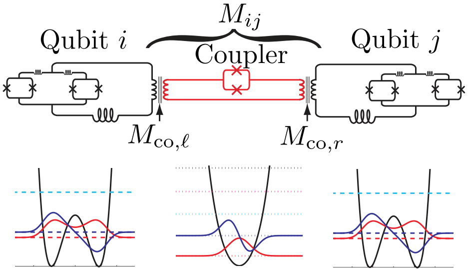
$$s_c < s(t) < 1$$



classical spin state

Superconducting circuit implementation

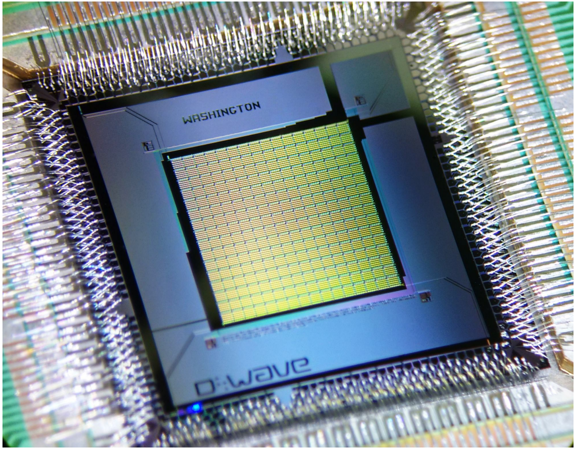


- Bistable rf SQUIDs act as flux qubits and monostable rf SQUIDs act as tunable couplers.

$$\mathcal{H} = \mathcal{H}_{\text{quantum}} + \mathcal{H}_{\text{classical}} = -\Gamma(s)\sum_i \sigma_i^x + \mathcal{J}(s)\left[\sum_i h_i\sigma_i^z + \sum_{<i,j>} J_{ij}\sigma_i^z\sigma_j^z\right]$$

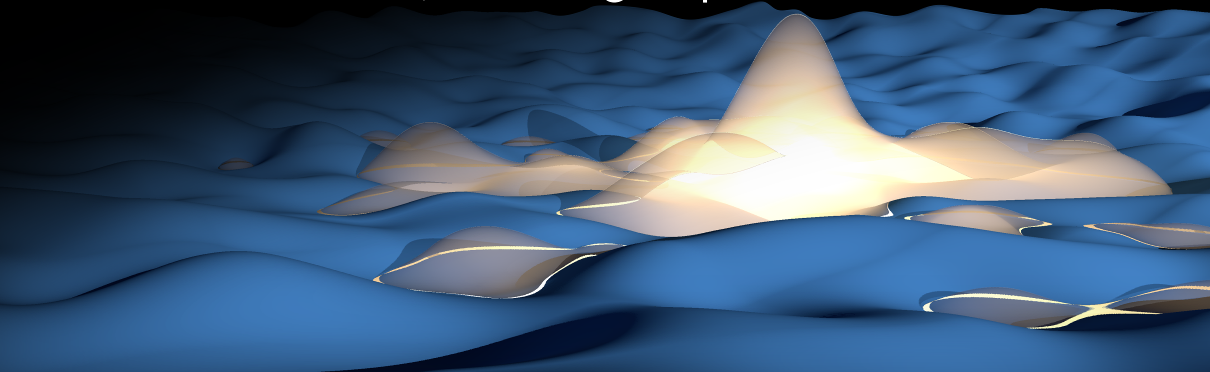
Harris *et al.* Phys. Rev. B, **82** 024511 (2010).

Scalable general-purpose QA processor

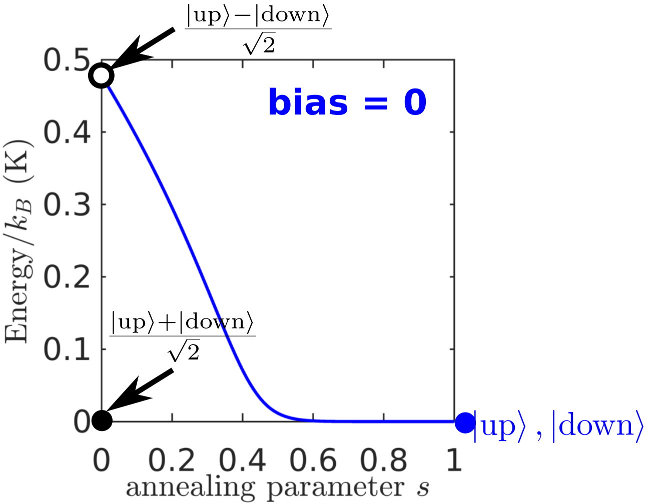


Bunyk *et al.*, Trans.Appl.Supercond. **24**, 1700110 (2014).
Whittaker *et al.*, J.Appl.Phys. **119**, 014506(2016).

QA of single qubits



Annealing a single qubit



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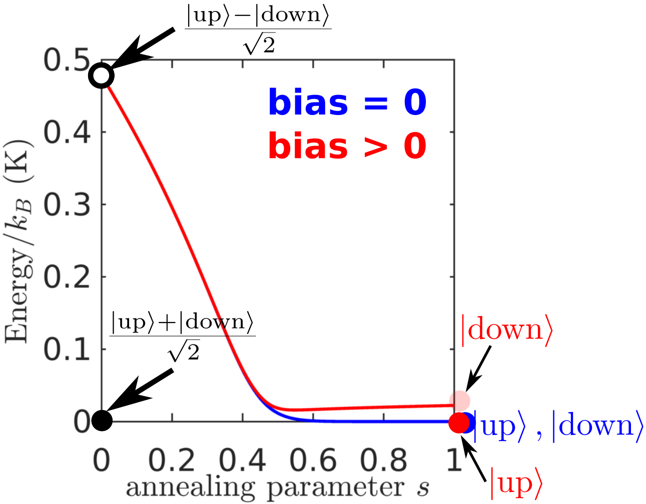

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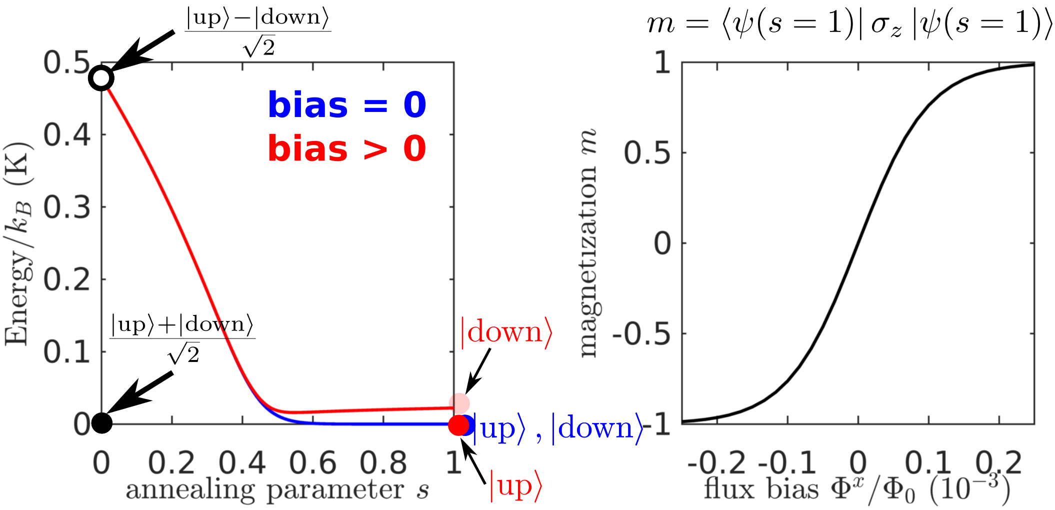

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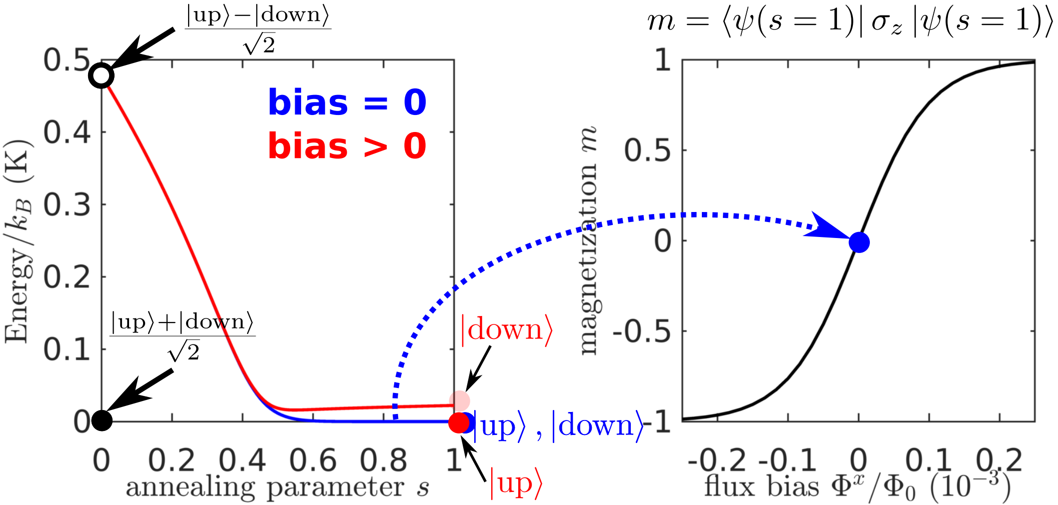

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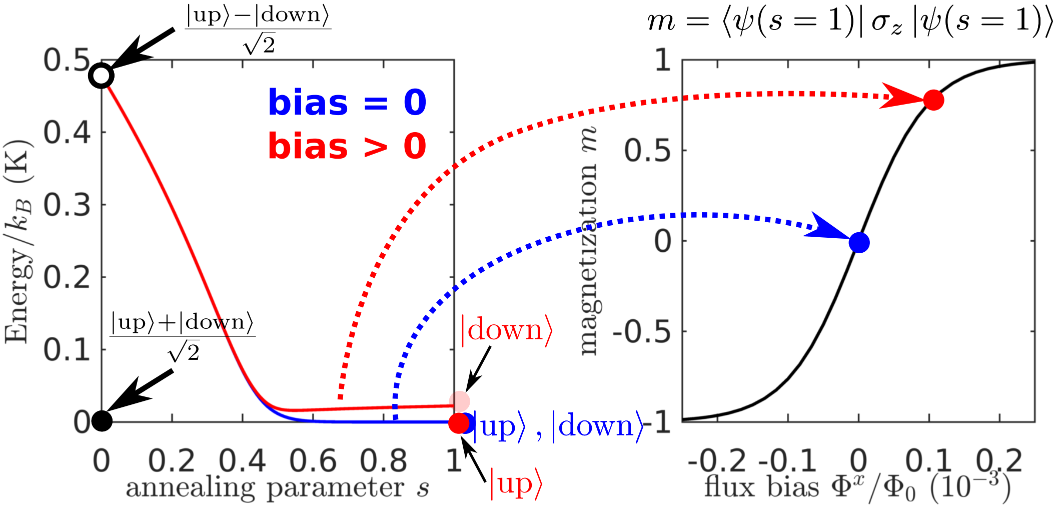

$$m = \langle \psi(s=1) | \, \sigma_z \, | \psi(s=1) \rangle$$

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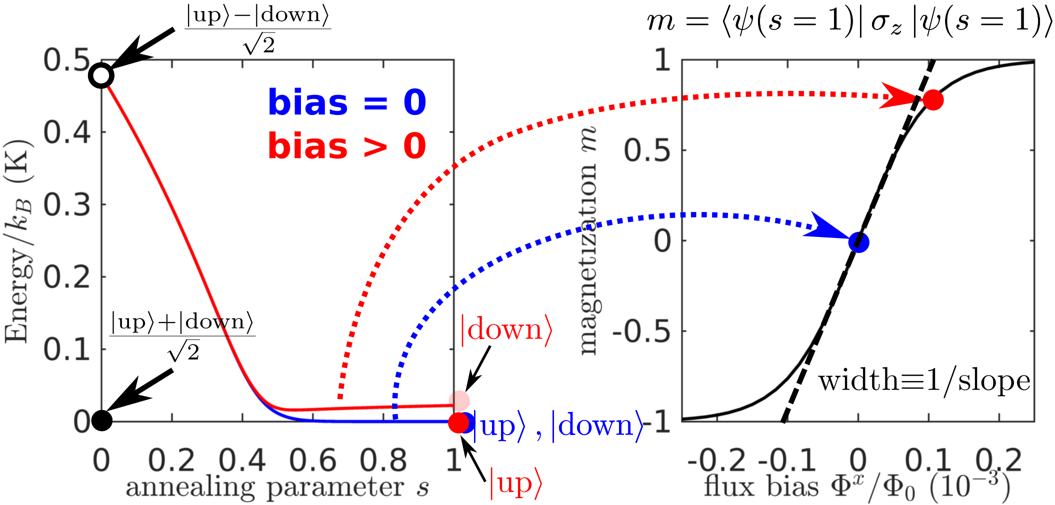

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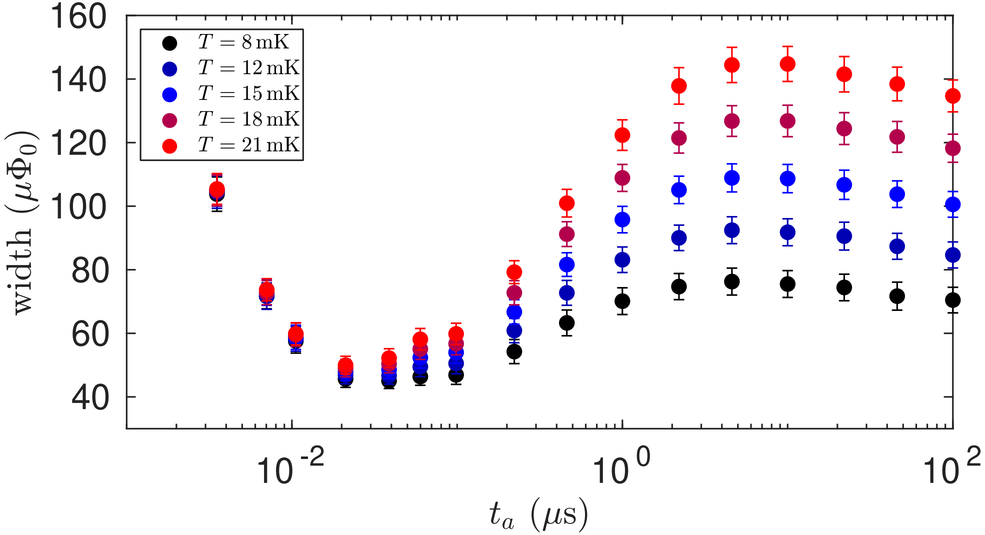
Different dynamical regimes



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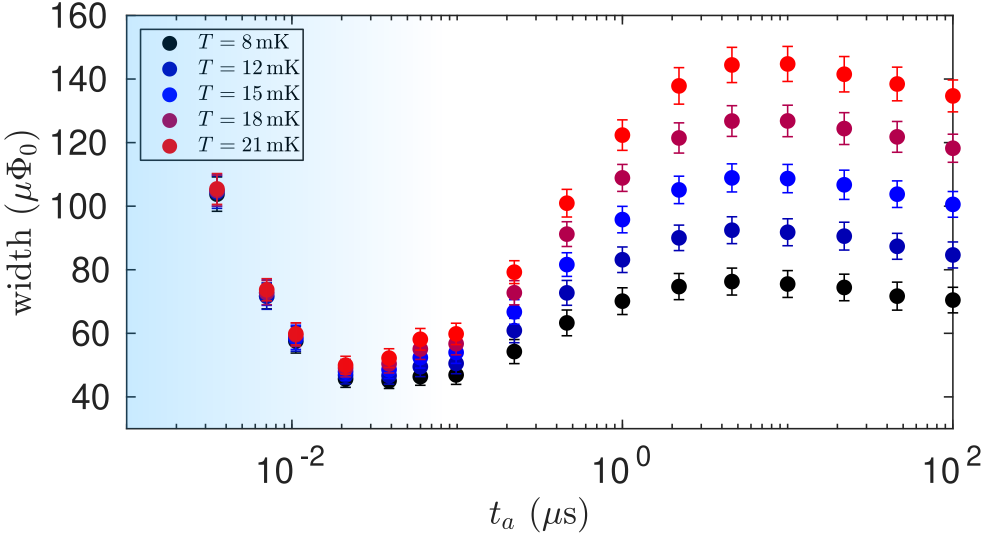

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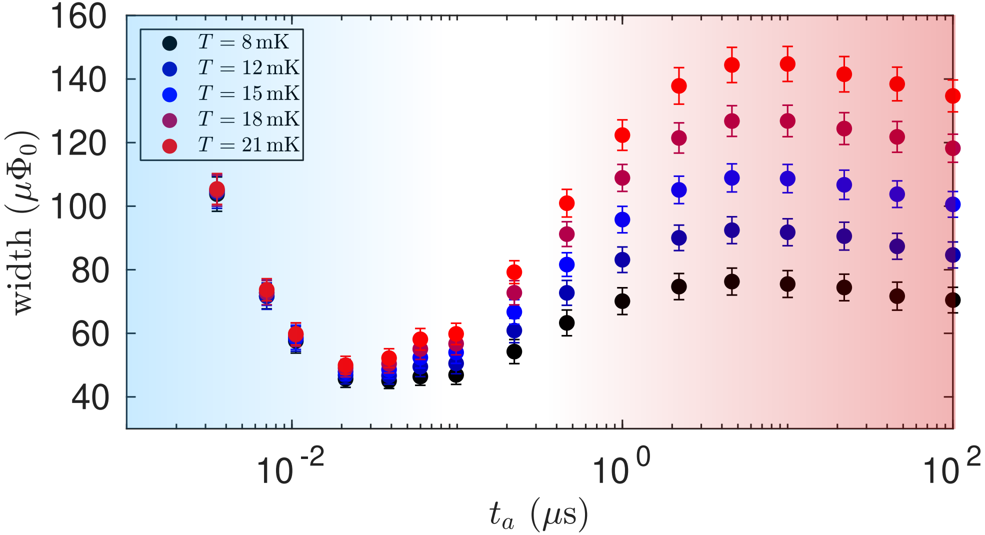

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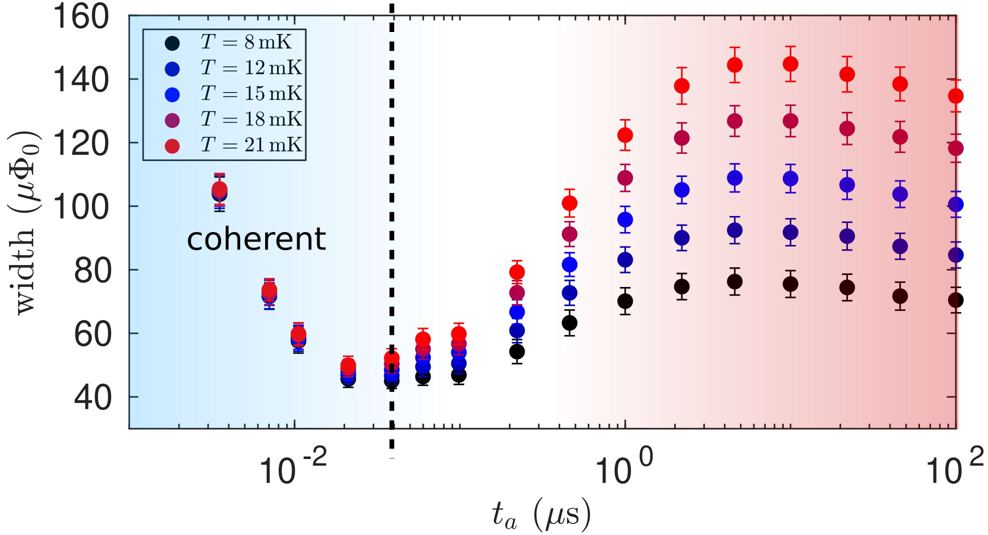

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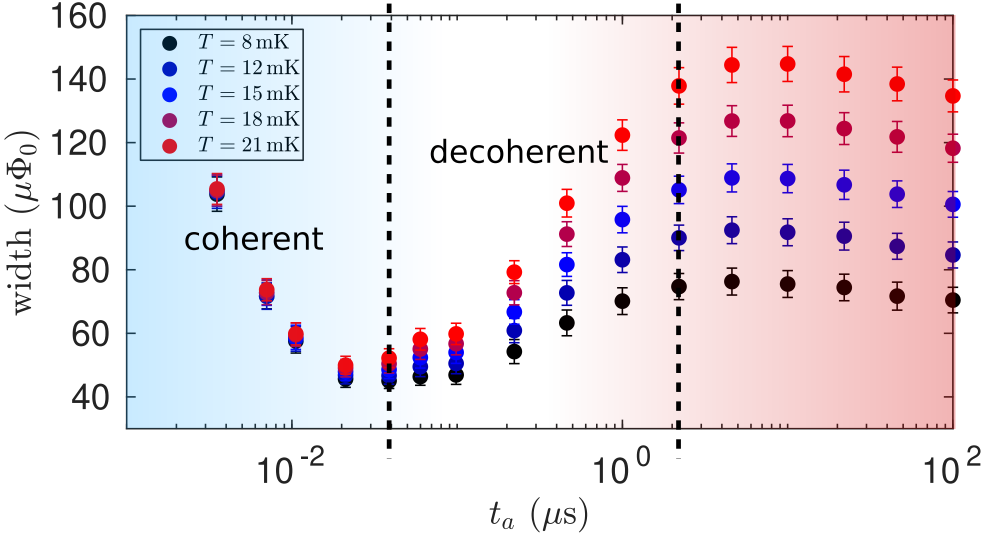

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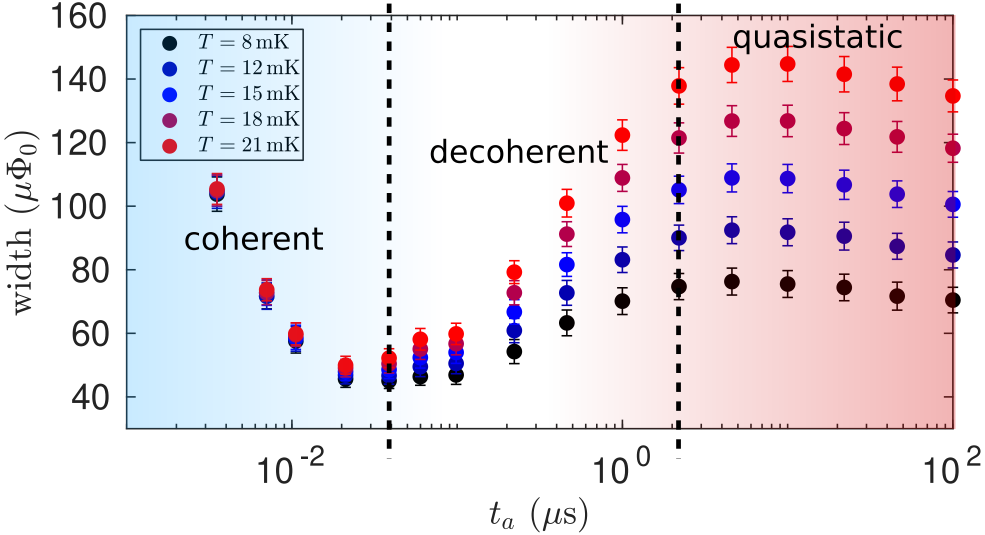

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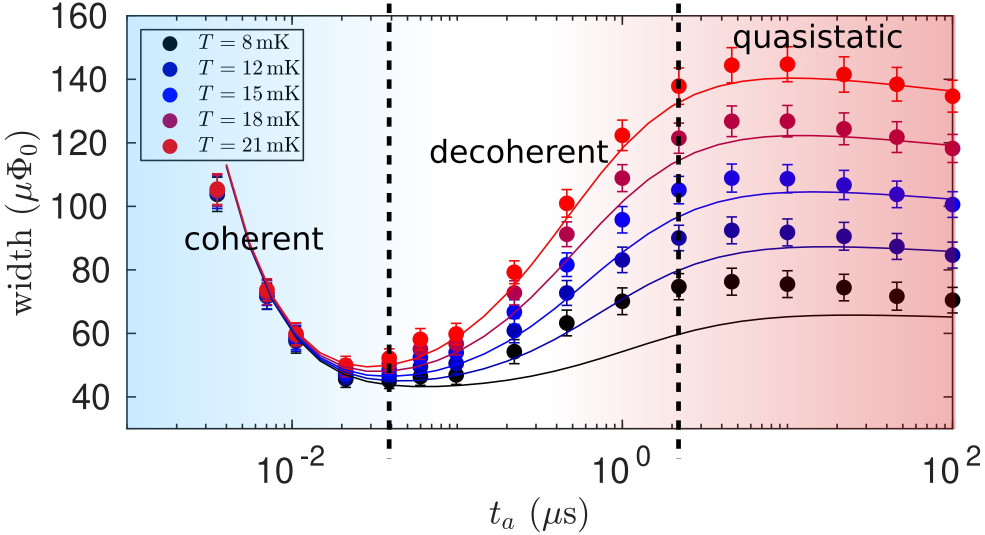
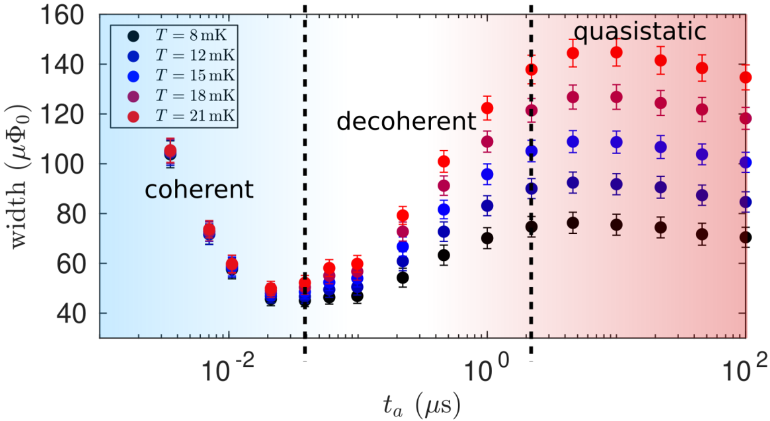


Outrunning the bear



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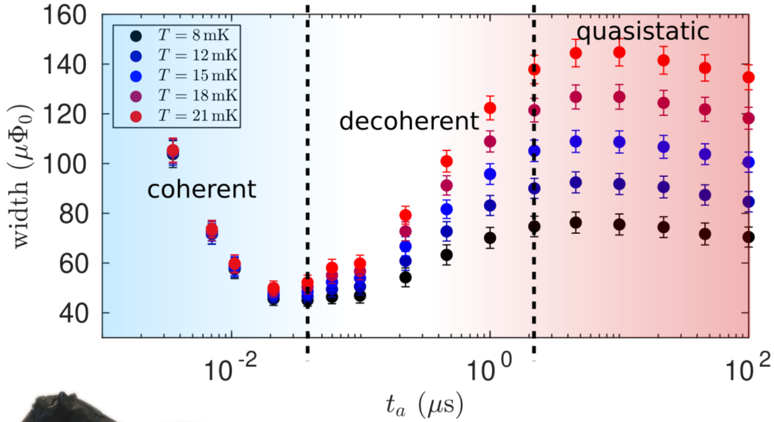
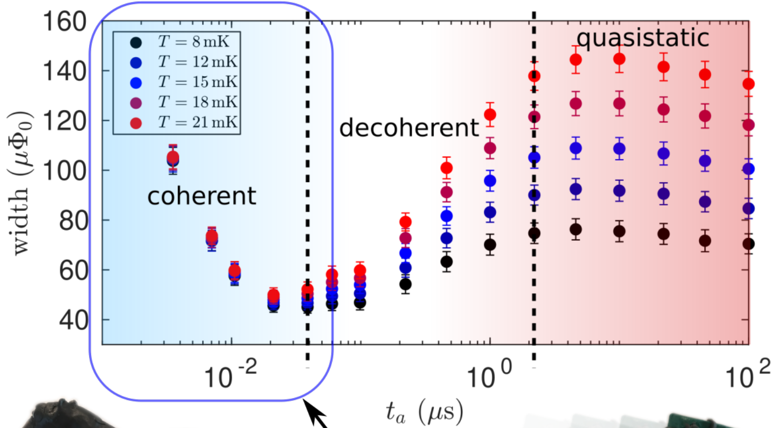
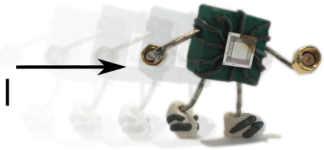


← Environment

Outrunning the bear



Fast Anneal



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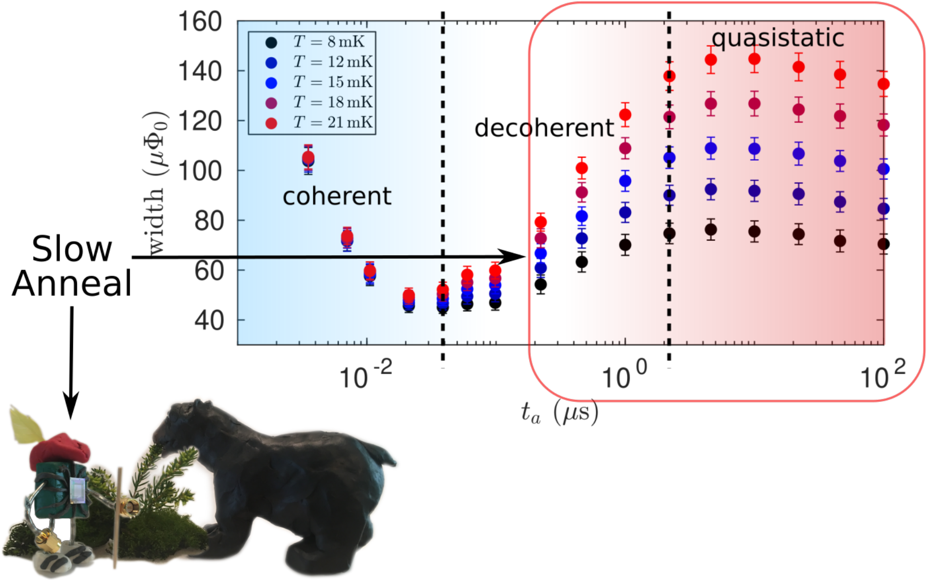

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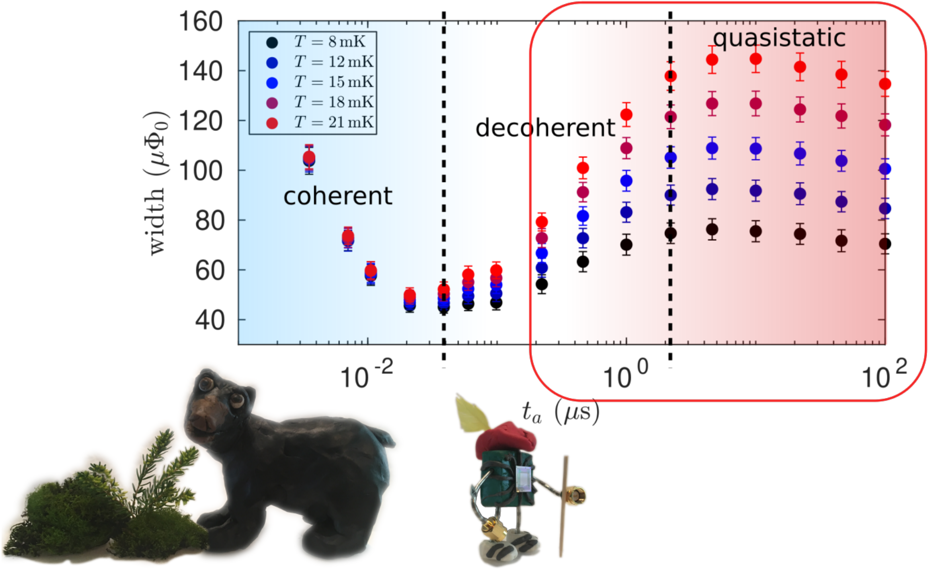

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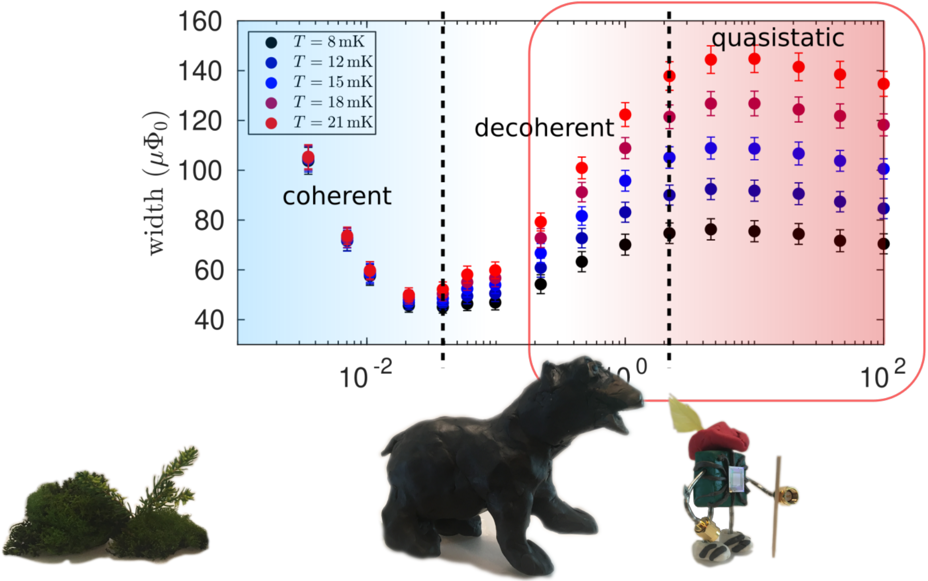

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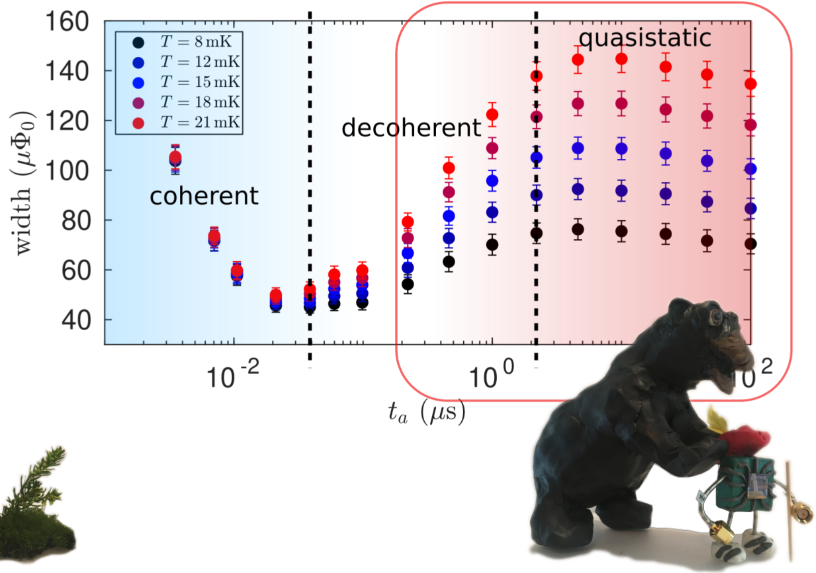
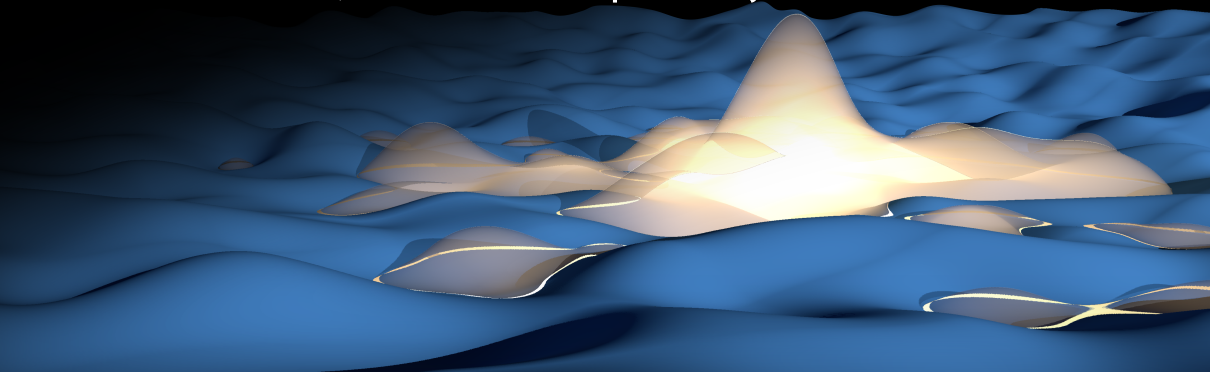
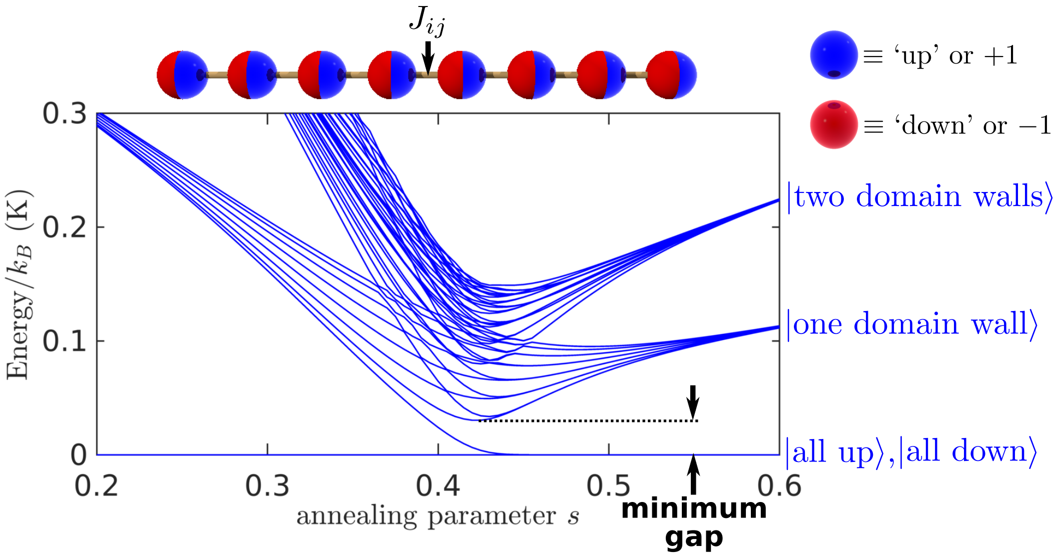


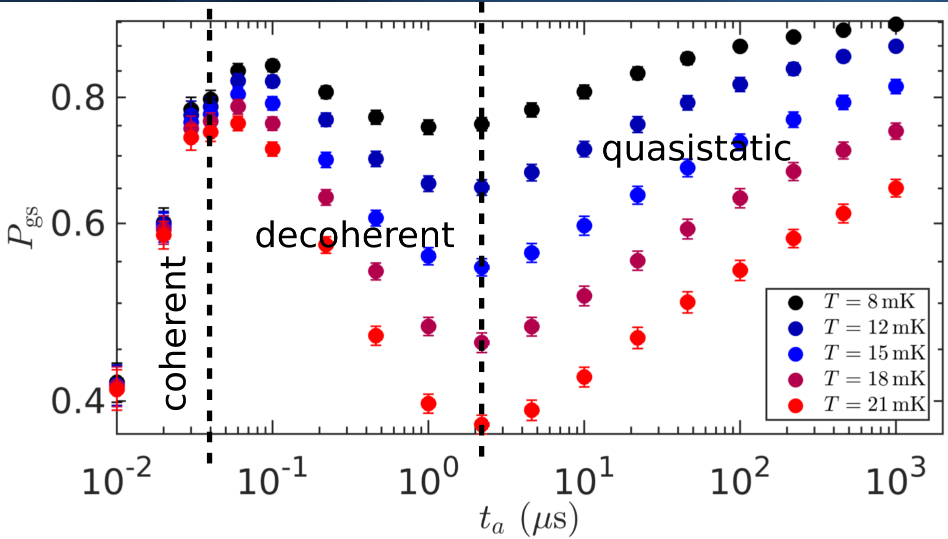
QA of multi-qubit systems



8-qubit ferromagnetic chain



Example results: $J_{ij} = 0.2$

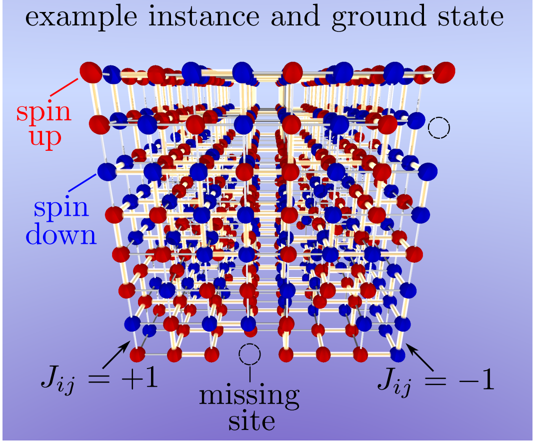


Cubic lattice problems

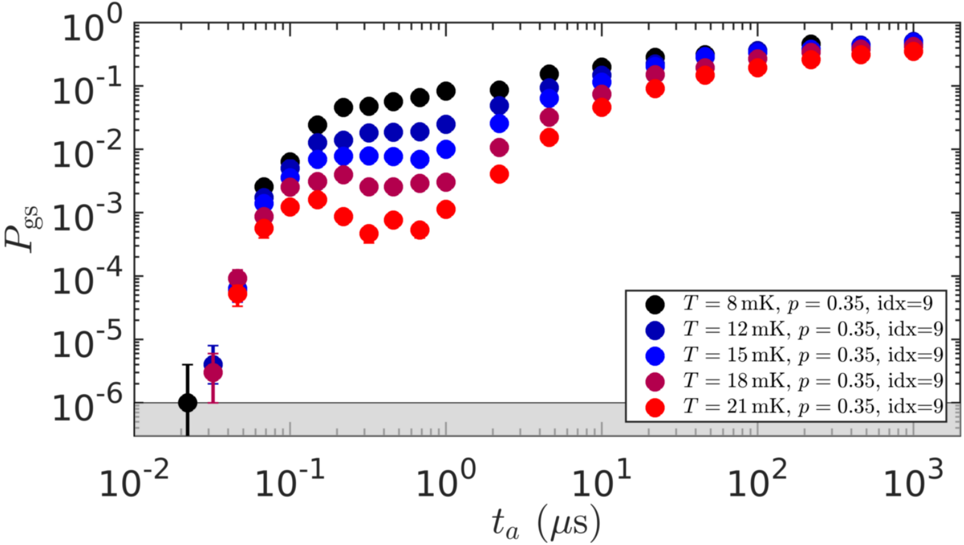
4 knobs to tune problem hardness:

- System size $L \times L \times L$.
- FM disorder density p.
- Energy scale $0 < |J_{ij}| < 1$.
- Number of missing sites.

L →coarse knob, p →fine knob



Example results: $L = 6$, $p = 0.35$



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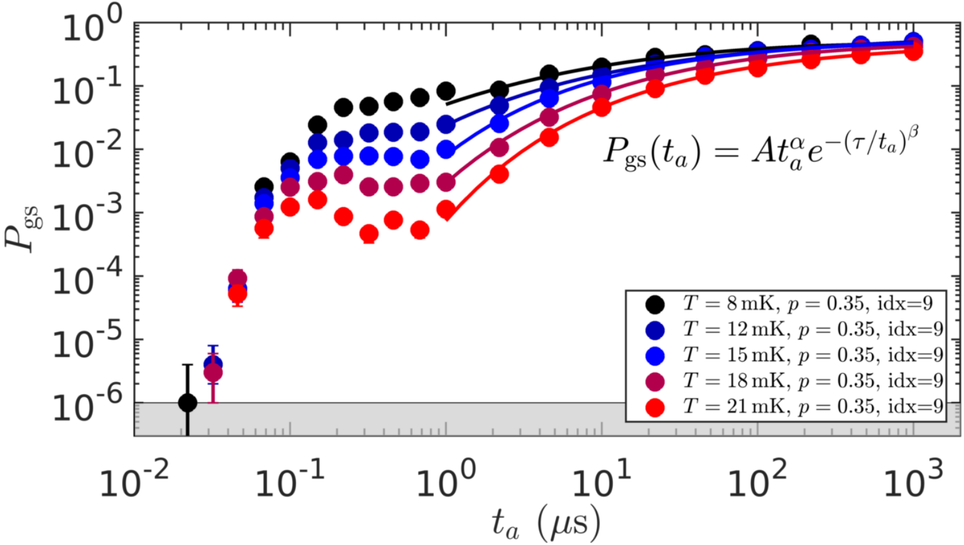

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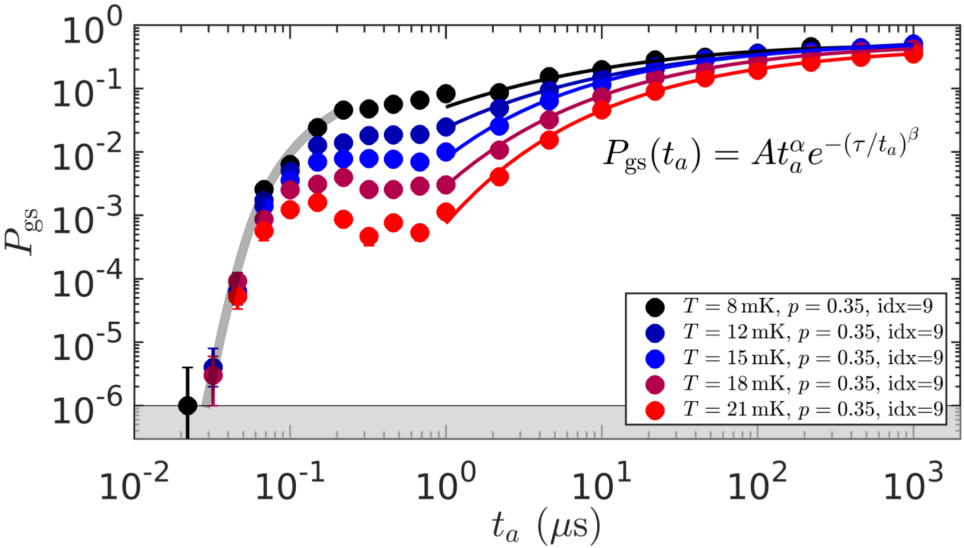

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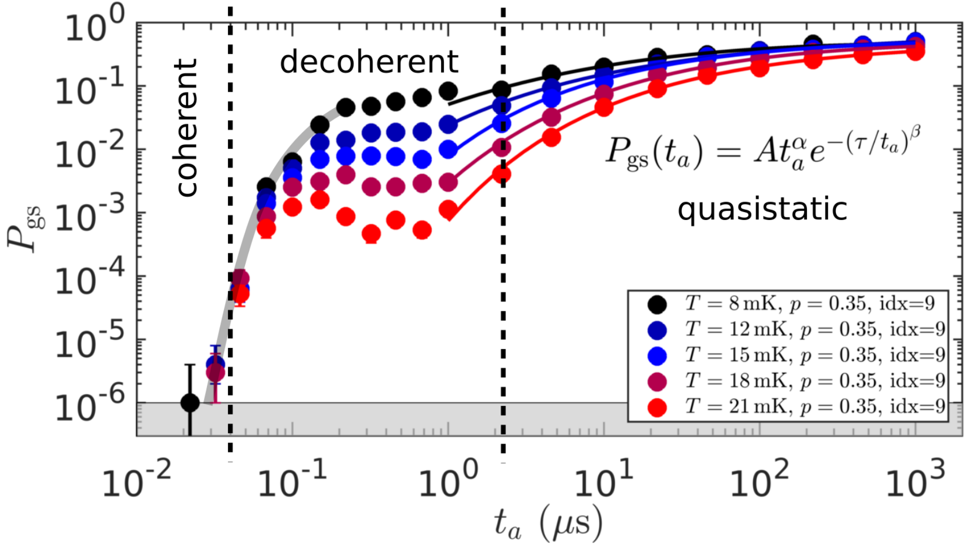
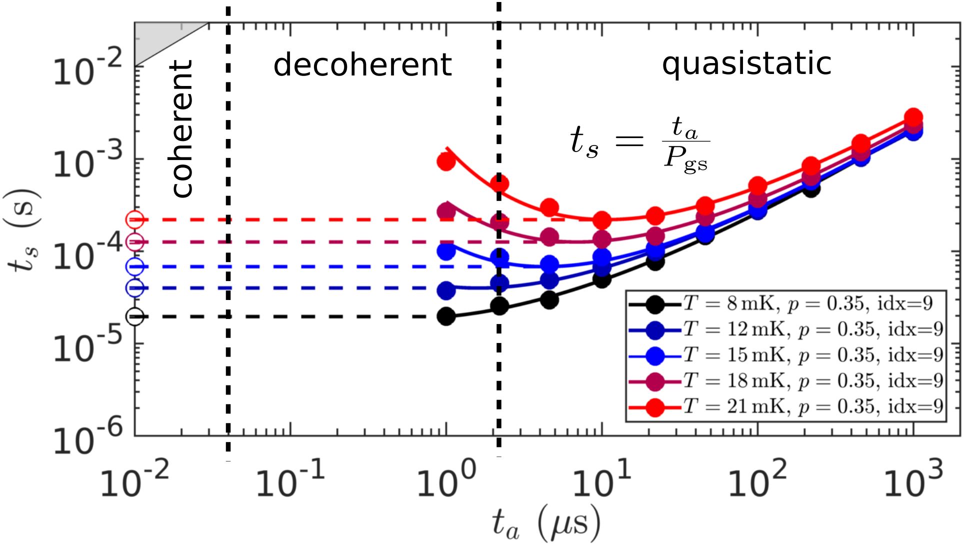


Is coherence advantageous?



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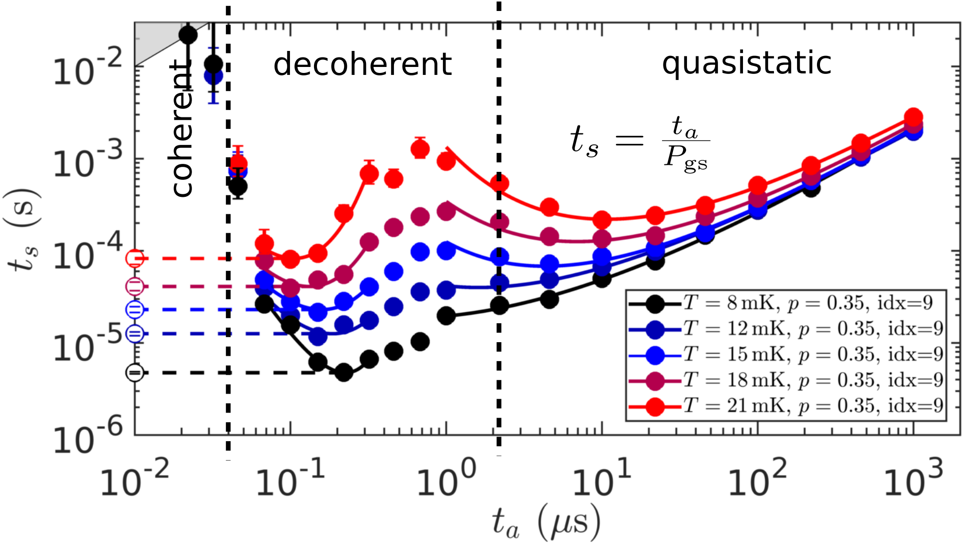
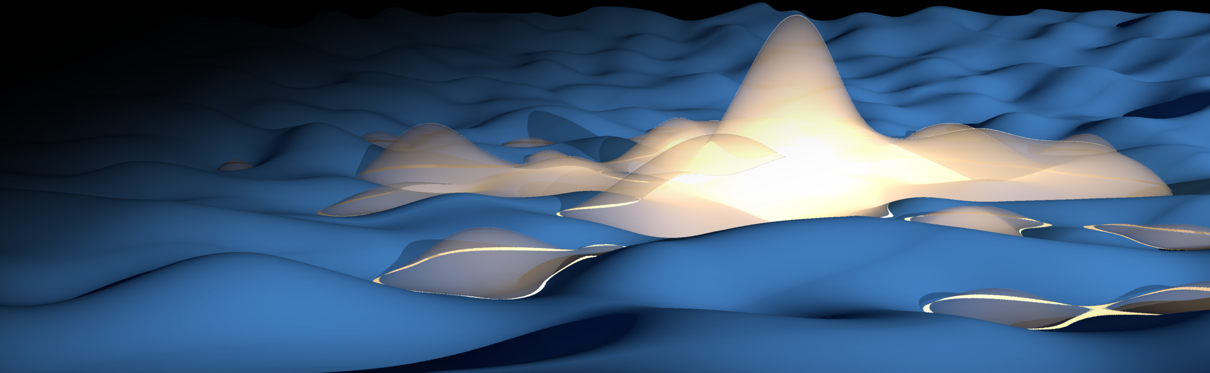


Conclusions



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Quo vadis?

- Higher coherence QPUs.
- Comparison to dynamical models.