MURI Review 2013: Control of quantum open systems: theory and experiment

Program manager:
Dr. Harry Chang, ARO

W911NF-11-1-0268

Meet the Team

Faculty: 12 (1 unfunded)
Industry: 1 (unfunded)
Postdocs: 14
Students: 14
Departments: EE (5), Phys. (5), Chem. (1), Math. (1)

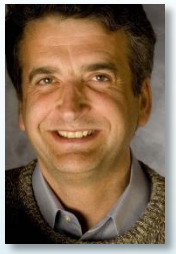
Daniel Lidar, PI
Prof.
EE (& Chem., Phys.)
3.5 postdocs
2 students

USC

Todd Brun
Assoc. Prof.
EE (& Phys.)
1 postdoc
3 students

Edmond Jonckheere
Prof.
EE (& Math.)
2 students

Lorenzo Campos-Venuti
Research Asst. Prof.
Physics
0.5 student



Anthony Levi
Prof.
EE (& Phys.)
2 students
(1 graduated)

Stephan Haas
Prof.
Physics
1+2*0.5 postdocs
1.5 students

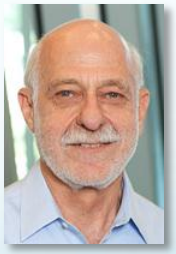
Paolo Zanardi
Prof.
Physics
1.5 postdocs
1 student

Network

Domenico D'Alessandro
Prof.
Mathematics
Iowa State
1 postdoc

Robert Kosut
Dr.
SC Solutions, Inc.
unfunded

Kurt Jacobs
Assoc. Prof.
Physics
UMass Boston
2 postdocs
1 student

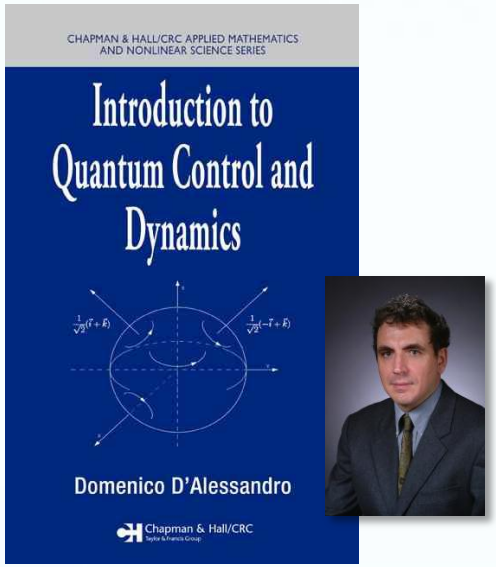


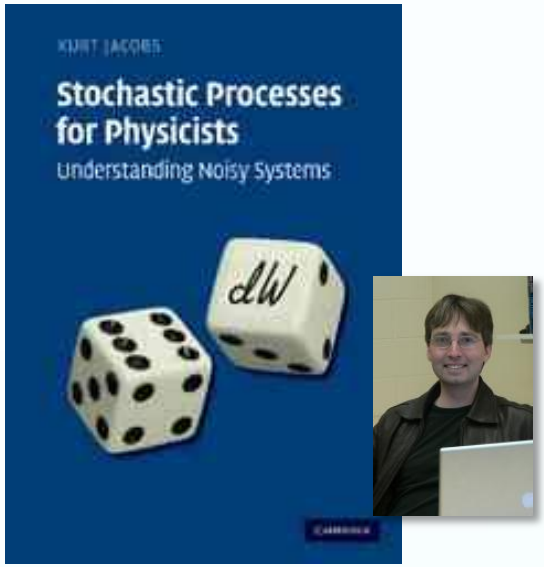
Herschel Rabitz
Prof.
Chemistry
Princeton U.
2 postdocs

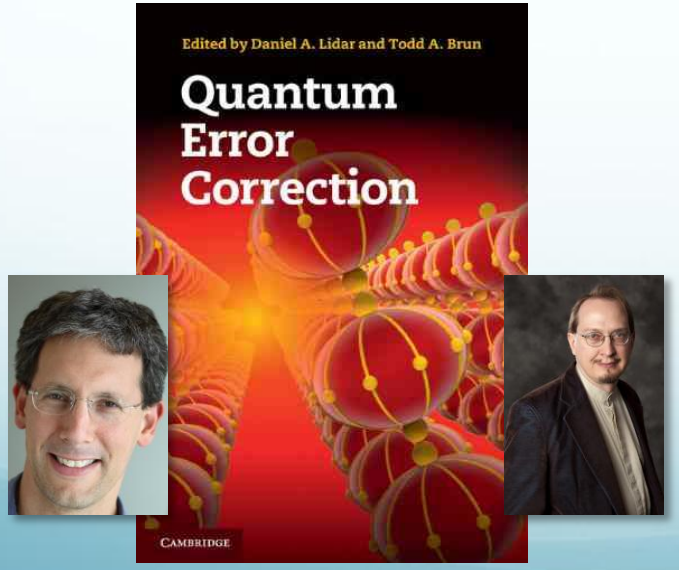
Alexander Korotkov
Prof.
EE
UC Riverside
2 postdocs
1 student

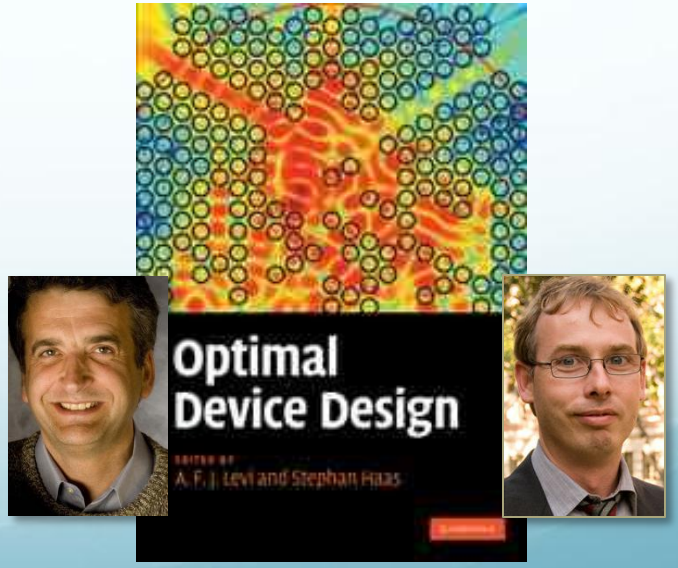
Howard Wiseman
Prof.
Physics
Griffiths U., Australia
unfunded

Some text/teference books by our MURI team members









Budget

Base Period - 3 Years			
07/31/12	7/31/13	5/31/14	TOTAL
$1,558,333 spent	$1,104,846 spent	$729,167 projected	$3,392,346

Optional Period - 2 Years			
06/01/14-09/30/14	10/01/14-09/30/15	10/01/15-05/31/16	TOTAL
$520,000 projected	$1,250,000 projected	$729,167 projected	$2,499,167 projected

TOTAL
Project Total
$5,891,513

Meetings

First MURI review/kickoff
Sep. 26, 2011
USC

Second MURI review
Nov. 28, 2012
USC

First MURI retreat
April 6-8, 2012
Claremont Hotel, Berkeley

Second MURI retreat
April 4-6, 2013
Canary Hotel, Santa Barbara

multiple collaborations among team members

- Various seminars by MURI team members at others' institutions
- Various mutual work visits
- Regular skype/email communication
- Collaborate using shared dropbox folders

Onward to the science

key MURI question

Can quantum systems be controlled and made to outperform classical systems in spite of decoherence?

Why is this area of research important?

Almost all quantum advantages (in computation, communication, cryptography, reaction yields, devices) require a very high degree of quantum coherence.

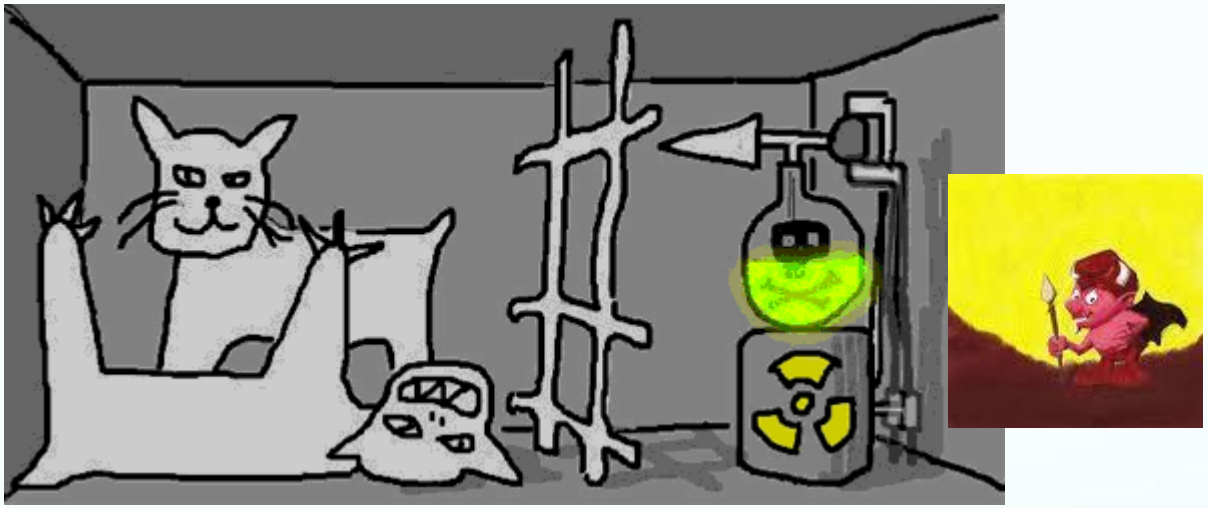
The advantage disappears when decoherence is too strong or isn't corrected for.

quantum superposition

- Quantum cat = dead AND alive $|\text{cat}\rangle = a|0\rangle + b|1\rangle$
- Classical cat = dead OR alive

prob.$=|a|^2$ prob.$=|b|^2$

Decoherence killed the superposition



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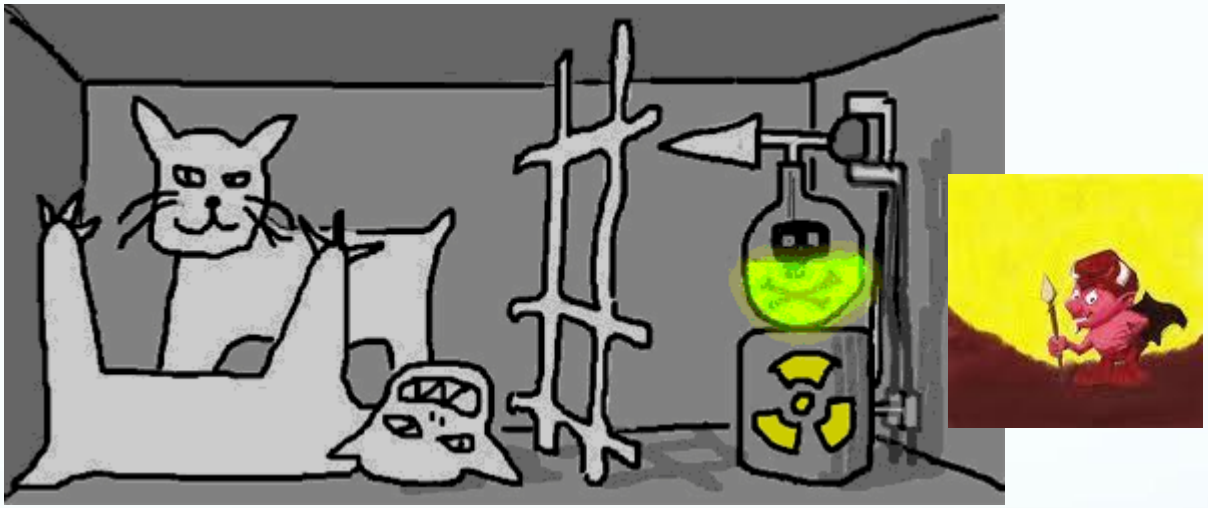

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key MURI objectives

Develop the theory required to analyze and enable control of open quantum systems

Experimentally demonstrate and verify control of open quantum systems

Scientific barrier:
Previous efforts were disparate; much of the work was done in isolation. The MURI enables & enhances communication and collaboration between leaders in the field and their groups.

Technical Approach: Theory

Mathematical tools:

- **Lie algebraic** (D'Allesandro, Jonckheere)
- **Convex optimization, dynamic programming** (Kosut)
- **Stochastic differential equations** (Brun, Jacobs, Wiseman)
- **Quantum probability theory** (Campos-Venuti, Korotkov, Zanardi)
- **Monte Carlo methods** (Haas)

Open quantum system formalism:

- **Markovian master equations** (Brun, Lidar, Zanardi)
- **Non-Markovian master equations** (Lidar)
- **Exact quantum dynamical maps** (Lidar, Campos-Venuti, Zanardi)
- **Quantum statistical mechanics** (Lidar, Zanardi)

Quantum control theory:

- **Control landscape analysis** (Jonckheere, Kosut, Rabitz)
- **Quantum error correction** (Brun, Lidar, Zanardi)
- **Quantum measurement theory** (Brun, Jacobs, Korotkov)

Technical Approach: Theory

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Experiment

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Quantum control theory:

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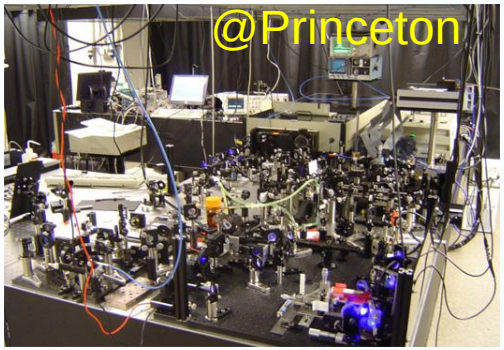
Technical Approach: Experimental

Gas phase control:
Quantum pathway manipulation using atomic Rb (Rabitz)

- Demonstrated control over interfering pathways
- Demonstrated quantum control mechanism analysis

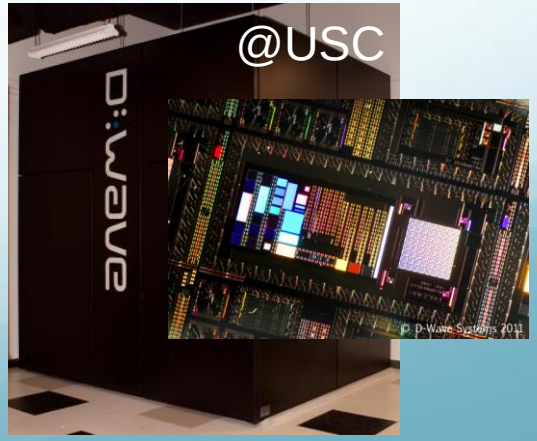


Meso-scale lasers:
- **Lasing at the quantum limit: 1 atom + 1 photon** (Levi)

- Demonstrated cavity with photon round trip time comparable to inverse spectral line width
- Experimental verification of transient cavity emission

D-Wave machine:
- **Quantum information processing** (Lidar)

- Demonstrated optimization via quantum annealing
- Benchmarking relative to classical processors
- Demonstrated quantum error correction



Accomplishments – small sample

Accomplishments – Theory of open quantum systems

New Journal of Physics
The open access journal for physics

Albash, Boixo, Lidar, Zanardi, 2012

Quantum adiabatic Markovian master equations

$$\frac{d}{dt}\rho_S = -i\left[H_S(t) + H_{LS}(t), \rho_S(t)\right] + \sum_{\omega} \gamma_{\alpha\beta}(\omega)\left(L_{\omega,\beta}(t)\rho_S L^{\dagger}_{\omega,\alpha}(t) + \frac{1}{2}\left\{L^{\dagger}_{\omega,\alpha}(t)L_{\omega,\beta}(t), \rho_S(t)\right\}\right)$$

Unitary evolution with bath-induced Lamb shift

Non-unitary dissipative dynamics

Lindblad operators:

$$L_{\alpha,ab} = |\varepsilon_a(t)\rangle\langle\varepsilon_a(t)|A_\alpha|\varepsilon_b(t)\rangle\langle\varepsilon_b(t)|$$

$a \neq b$: relaxation

$a = b$: dephasing

dephasing/relaxation rates:

$$\gamma_{\alpha\beta}(\omega_{ba}(t)) = \int_{-\infty}^{\infty} d\tau e^{i\omega_{ba}(t)\tau}\langle B_\alpha(\tau)B_\beta(0)\rangle$$

Needed to describe quantum control experiments with slowly varying controls

Accomplishments – Theory input to control experiment

LETTER

Nature **490**, 77 (2012)

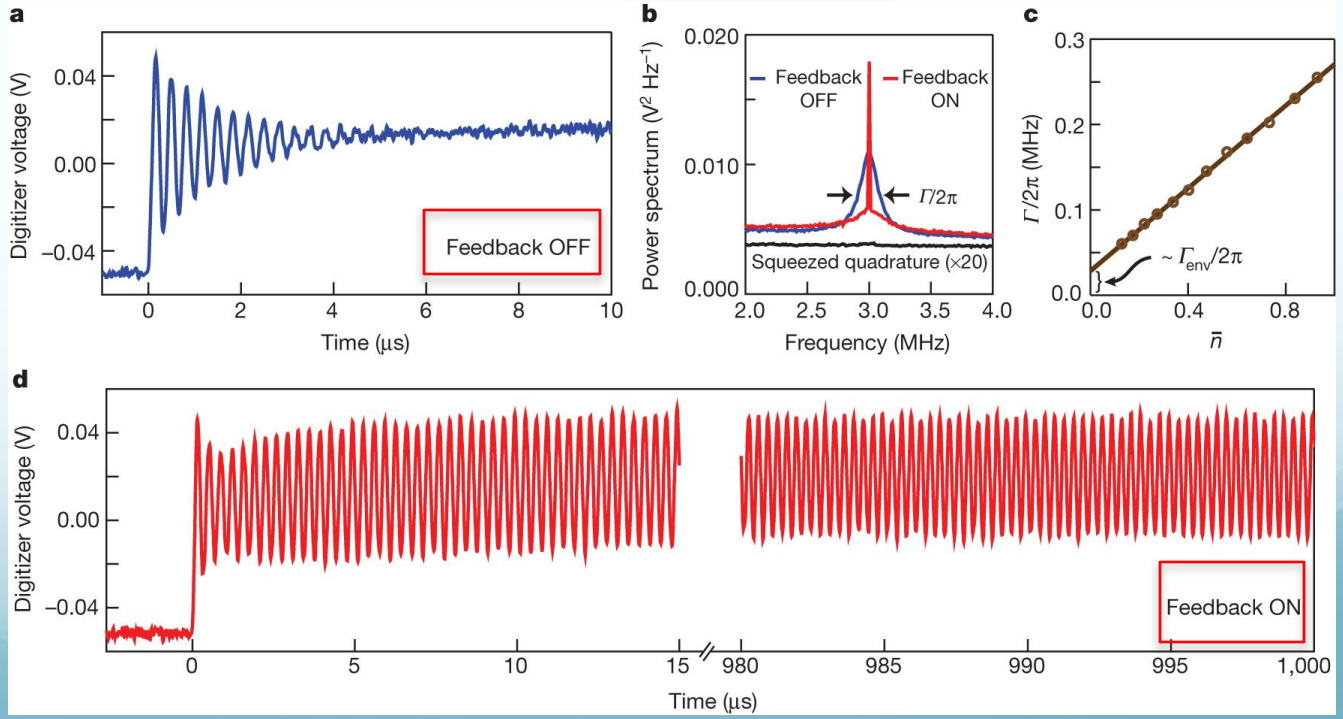
doi:10.1038/nature11505

Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback

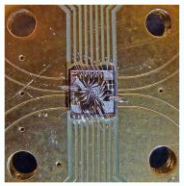
R. Vijay[1], C. Macklin[1], D. H. Slichter[1]†, S. J. Weber[1], K. W. Murch[1], R. Naik[1], A. N. Korotkov[2] & I. Siddiqi[1]

Superconducting qubit coupled to a microwave cavity.

Number of photons in cavity measured and kept constant; sustains qubit coherence.



Accomplishments – Theory input to control experiment



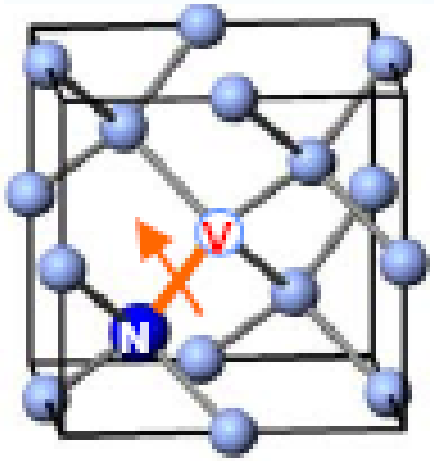
LETTER

Nature **484**, 82 (2012)

doi:10.1038/nature10900

Decoherence-protected quantum gates for a hybrid solid-state spin register

T. van der Sar[1], Z. H. Wang[2], M. S. Blok[1], H. Bernien[1], T. H. Taminiau[1], D. M. Toyli[3], D. A. Lidar[4], D. D. Awschalom[3], R. Hanson[1] & V. V. Dobrovitski[2]



- NV@diamond: nuclear and electron spin qubits (room temperature)

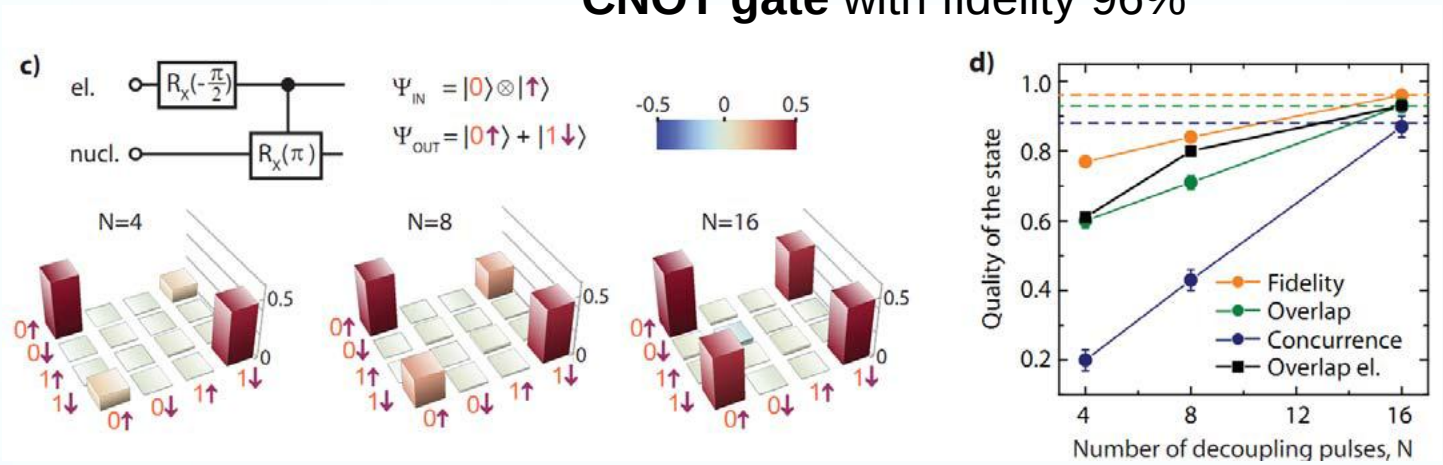
$$H_{\mathrm{hf}} = A_0 S_0^z I_0^z + A_\perp (S_0^x I_0^x + S_0^y I_0^y)$$

- qubit 1: electron spin S_0 : *fast response, short coherence time, convenient to manipulate*
- qubit 2: nuclear spin I_0 : *slow response, long coherence time, good "quantum memory"*

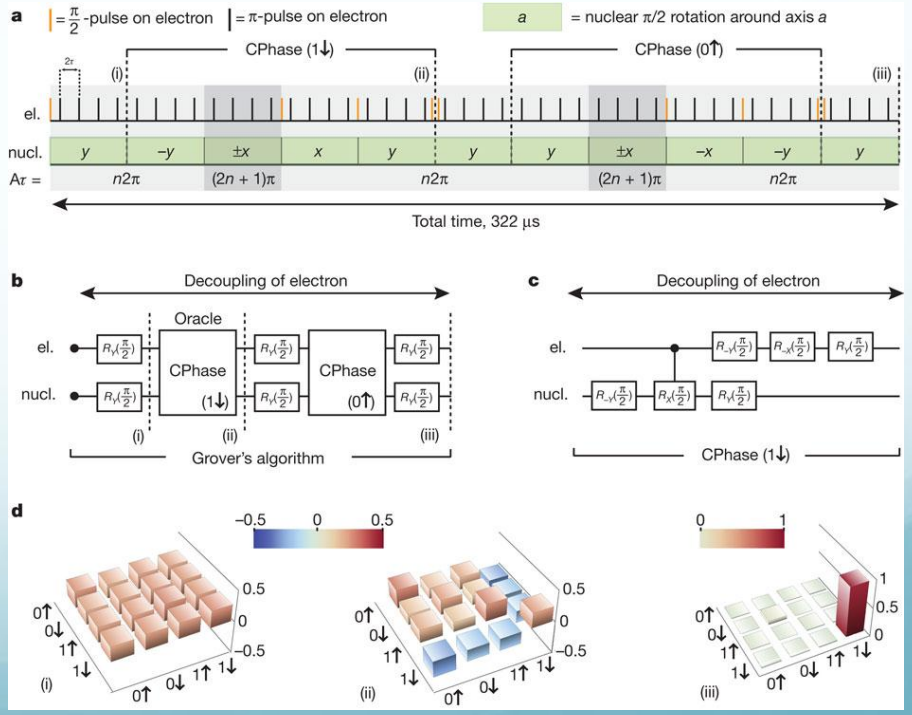
Control principle: apply dynamical decoupling to electron , synchronously drive nucleus

Accomplishments – Theory input to control experiment

CNOT gate with fidelity 96%



Grover's search algorithm executed with decoherence-protected gates:



Total time: 322 μs
electron T_2=251 μs, T_2*~ 1 μs

Nature **484**, 82 (2012)

Accomplishments – Theory coupled to control experiment

PRL **110,** 223601 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

Manipulating Quantum Pathways on the Fly

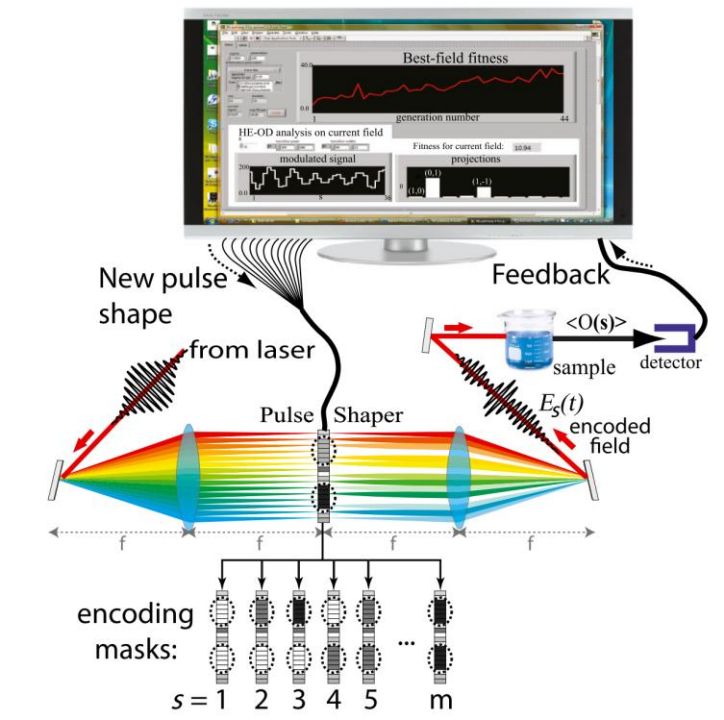
Roberto Rey-de-Castro,[1] Zaki Leghtas,[1,2] and Herschel Rabitz[1]

[1]*Department of Chemistry, Princeton University, Princeton, New Jersey 08544, USA*

[2]*INRIA Paris-Rocquencourt Domaine de Voluceau, BP105 78153 Le Chesnay Cedex, France*

(Received 28 February 2012; published 29 May 2013)

Allows steering the quantum amplitude down one path vs. another on the way to the target



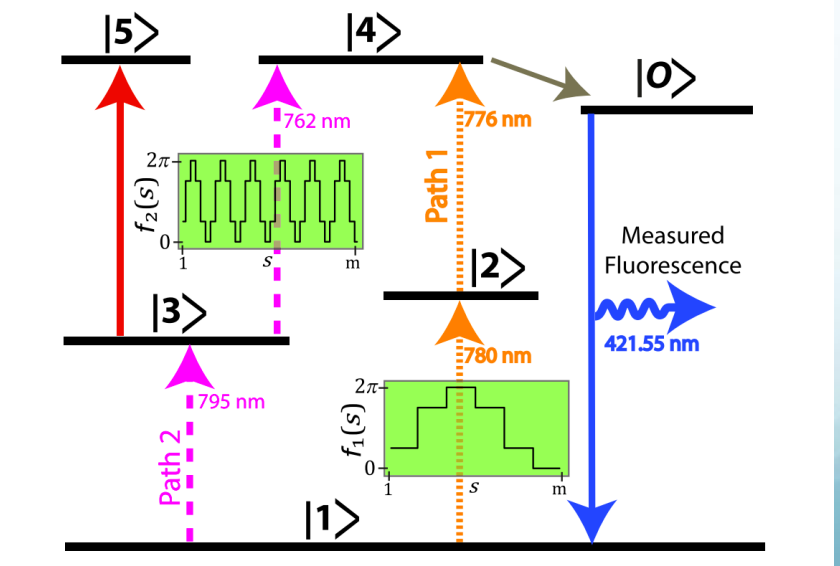


FIG. 2 (color online). Energy level diagram and transitions for atomic Rb. States $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$, $|5\rangle$, and $|O\rangle$ correspond to the levels $5S_{1/2}$, $5P_{1/2}$, $5P_{3/2}$, $5D_{3/2}$, $5D_{5/2}$, and $6P_{1/2}$, respectively.

Publications: published

Published or Accepted papers	Title	Authors
Nature 484, 82 (2012)	Decoherence-Protected Quantum Gates for a Hybrid Solid-State Spin Register	T. van der Sar, Z.H. Wang, M.S. Blok, H. Bernien, T.H. Taminiau, D.M. Toyli, **D.A. Lidar**, D.D. Awschalom, R. Hanson, and V.V. Dobrovitski
Nature 490, 77 (2012)	Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback	R. Vijay, C. Macklin, D.H. Slichter, S.J. Weber, K.W. Murch, R. Naik, **A.N. Korotkov**, and I. Siddiqi
Nature 490, 43 (2012)	Quantum Physics: Cruise Control for a Qubit	**H. Wiseman**
Nature Phys. 8, 107 (2012)	Entanglement preservation: the Sleeping Beauty approach	**A. N. Korotkov**
Nature Comm. 4, 2067 (2013)	Experimental Signature of Programmable Quantum Annealing	S. Boixo, T. Albash, F. Spedalieri, N. Chancellor, **D.A. Lidar**
Phys. Rev. Lett. 108, 080501 (2012)	Zeno Effect for Quantum Computation and Control	G. A. Paz-Silva, A. T. Rezakhani, J. Dominy and **D. A. Lidar**
Phys. Rev. Lett. 109, 190403 (2012)	Operational Dynamic Modeling Transcending Quantum and Classical Mechanics	D. Bondar, R. Cabrera, R. Lompay, M. Ivanov and **H. Rabitz**
Phys. Rev. Lett. 110, 223601 (2013)	Manipulating Quantum Pathways on the Fly	R. Rey-de-Castro, Z. Leghtas and **H. Rabitz**
Phys. Rev. Lett. 110, 210501 (2013)	Catch-Disperse-Release Readout for Superconducting Qubits	E. A. Sete, A. Galiautdinov, E. Mlinar, J. M. Martinis, and **A. N. Korotkov**
Phys. Rev. Lett. 110, 157207 (2013)	Absolute Dynamical Limit to Cooling weakly-Coupled quantum Systems	X. Wang, Sai Vinjanampathy, Frederick W. Strauch, and **K. Jacobs**
Phys. Rev. Lett. 110, 170404 (2013)	Onthological models predictively inequivalent to quantum theory	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
IEEE Trans. Auto. Control, 57, No. 8 (2012)	Indirect controllability of quantum systems; A study of two interacting quantum bits	**D.D'Alessandro** and R. Romano
IEEE Trans. Auto. Control (accepted)	Zero forcing, linear and quantum controllability for systems evolving on networks	D. Burgarth, **D. D'Alessandro**, L. Hogben, S. Severini and M. Young
New J. Phys. 14, 095025 (2012)	Using the J1-J2 quantum spin chain as an adiabatic quantum data bus	N. Chancellor and **S. Haas**
New J. Phys. 14, 123016 (2012)	Quantum Adiabatic Markovian Master Equations	T. Albash, S. Bioxo, **D. A. Lidar, and P. Zanardi**
New J. Phys. 15, 053002 (2013)	Error-transparent evolution: the ability of multi-body interactions to bypass decoherence	O. Vy, X. Wang, and **K. Jacobs**
New J. Phys., 15, 025032 (2013)	Time Resolved Quantum Process Tomography Using Hamiltonian-encoding and Observable-decoding	R. Rey-de-Castro, R. Cabrera, D.I. Bondar, and **H. Rabitz**
Phys. Rev. A 86, 022107 (2012)	A general theorem on local parts of hidden variable models	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
Phys. Rev. A 86, 022116 (2012)	Quantum and Superquantum Nonlocal Correlations	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
Phys. Rev. A 86, 022107 (2012)	A general theorem on local parts of hidden variable models	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
Phys. Rev. A 86, 013405 (2012)	Singularities of Quantum Control Landscapes	R. Wu, R. Long, J. Dominy (**Lidar** group), T.-S. Ho, and **H. Rabitz**
Phys. Rev. A 86, 012333 (2012)	Simplified quantum error detection and correction for superconducting qubits	K. Keane and **A. N. Korotkov**
Phys. Rev. A 86, 052324 (2012)	Ensembles of physical states and random quantum circuits on graphs	Alioscia Hamma, Siddhartha Santra, **P. Zanardi**
Phys Rev A, 86, 062309 (2012)	Exploring the Tradeoff Between Fidelity and Time Optimal Control of Quantum Unitary Transformations	K.W. Moore Tibbetts, C. Brif, M.D. Grace, A. Donovan, D.L. Hocker, T.S. Ho, R. Wu, and **H. Rabitz**
Phys. Rev. A 87, 012338 (2013)	Numerical method for finding decoherence-free subspaces and its applications	X. Wang, M. Byrd, and **K. Jacobs**
Phys. Rev. A 87, 032117 (2013)	Non-Markovian quantum input-output networks	J. Zhang, Y.-X. Liu, R.-B. Wu, **K. Jacobs**, and F. Nori
Phys. Rev. A 87, 042321 (2013)	Scalable universal holonomic quantum computation realized with an adiabatic quantum data bus and potential implementation using superconducting flux qubits	N. Chancellor and **S. Haas**
Phys. Rev. A 88, 012103 (2013)	Coarse Graining Can Beat the Rotating-Wave Approximation in Quantum Markovian Master Equations	C. Majenz, T. Albash, H.P. Breuer, and **D.A. Lidar**
Phys Rev A, 88, 012116 (2013)	Conceptual Inconsistencies in Finite-dimensional Quantum and Classical Mechanics	D.I. Bondar, R. Cabrera, and **H. Rabitz**
Phys. Rev. A 87, 032108 (2013)	Equilibration times in clean and noisy systems	**L. Campos Venuti**, S. Yeshwanth, and **S. Haas**
Phys. Rev. B 84, 035130 (2011)	Propagation of disturbances in degenerate quantum systems	N. Chancellor and **S. Haas**
Phys. Rev. B 87, 184302 (2013)	Non-Markovian equilibration controlled by symmetry breaking	N. Chancellor, C. Petri, **S. Haas**
Phys. Rev. E 86, 040106(R) (2012)	Quantum measurement and the first law of thermodynamics: the energy cost of measurement is the work value of the acquired information	K. Jacobs
Phys. Rev. E 87, 012106 (2013)	Gaussian Equilibration	L. Campos Venuti, P. Zanardi

Publications: published

Published or Accepted papers	Title	Authors
Scientific Reports 3, 1530 (2013)	Optimally Combining Dynamical Decoupling and Quantum Error Correction	G.A. Paz Silva and **D. A. Lidar**
Scientific Reports 3, 1394 (2013)	No-Go Theorem for Passive Single-rail Linear Optical Quantum Computing	L.-A. Wu, P. Walther, and **D. A. Lidar**
J. Chem. Phys. 137, 134113 (2012)	Exploring Constrained Quantum Control Landscapes	K. Moore and **H. Rabitz**
J. Phys. A: Math Theor, 45, 485303 (2012)	Control Landscapes for Open System Quantum Operations	R. Wu and **H. Rabitz**
J. Phys. A: Math. Theor. 45, 232001 (2012)	On a proposal of superluminal communication	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
J. Phys. A: Math. Theor., 46 045301, 2013	Control of a two level quantum system in a coherent feedback scheme	F. Albertini and **D. D'Alessandro**
J. Phys. A: Math. Theor. 46, 075306 (2013)	Analysis of the Quantum Zeno Effect for Quantum Control and Computation	J. Dominy, G. Paz-Silva, A. T. Rezakhani, and **D.A. Lidar**
J. Math. Phys. 53, 122207 (2012)	Universality Proof and Analysis of Generalized Nested Uhrig Dynamical Decoupling	W. J. Kuo, G. A. Paz-Silva, G. Quiroz, and **D. A. Lidar**
J. Stat. Mech. P04023 (2013)	Entanglement susceptibility: Area laws and beyond	P. Zanardi and L. Campos Venuti
Phys. Lett. A 377, 1854 (2013)	Probability density of quantum expectation values	L. Campos Venuti, P. Zanardi
Found. of Phys. 43, 881 (2013)	About possible extensions of quantum theory	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
Physica E 44, (2012)	Optimal design of a semiconductor heterostructure tunnel diode with nonlinear current-voltage characteristic	K. C. Magruder and **A.F.J. Levi**
Systems & Control Lett. 62, 188193 (2013)	Equivalence between indirect controllability and complete controllability for quantum systems	D. D'Alessandro
Automatica	Quantum Walks and Random Walks	**D. D'Alessandro** and S. Simsek
Math. Control Signals Syst. (2012) 24:321–349	Controllability of quantum walks on graphs	F. Albertini and **D. D'Alessandro**
Int. J. Mod. Phys. B 27, 1245011 (2013)	Classical, quantum and superquantum correlations	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
J. Phys.: Conf. Ser. 442, 012002 (2013)	On the completeness of quantum mechanics and the interpretation of the state vector	GianCarlo Ghirardi, Raffaele Romano (**D'Alessandro** group)
Quantum Inf. Proc. 12, 1515 (2013)	Differential topology of adiabatically controlled quantum processes	**E. A. Jonckheere**, A. T. Rezakhani, and F. Ahmad
Proceedings Conference on Decision & Control (2012)	Indirect Controllability and Indirect Observability of Quantum Mechanical Systems	**D. D'Alessandro** and R. Romano
Proceedings Conference on Decision & Control (2013)	Sampled-data Design for Robust Decoherence Control of a Single Cubit	D. Dong, I.R. Peterson, and **H. Rabitz**
Proceedings Conference on Decision & Control (2013)	Adaptive quantum control via approximate fidelity estimation	**R.L. Kosut, H. Rabitz**, Matthew Grace
Proceedings of 2011 Les Houches summer school	Quantum Bayesian approach to circuit QED measurement	A. N. Korotkov
International Symposium on Control, Communications and Signal Processing (2012)	Curvature of quantum rings	**E. Jonckheere**, F. C. Langbein, and S. G. Schirmer
Emergence, Complexity and Computation, H. Richter, ed. (Springer)	Fundamental Principles of Control Landscapes with Applications to Quantum Mechanics, Chemistry and Evolution	R. Wu, T. Ho, K. Moore and **H. Rabitz**

Publications: submitted

Submitted Papers	Title	Authors
Nature Phys., arXiv:1304.4595	Quantum Annealing With More Than One Hundred Qubits	S. Boixo, T. Ronnow, S. Isakov, Z. Wang, D. Wecker, **D.A. Lidar**, J. Martinis, and M. Troyer
Phys. Rev. Lett., arXiv:1304.4608	Modulated Electromechanics: Large Enhancements of Nonlinearities	Jie-Qiao Liao, **K. Jacobs**, Franco Nori, Raymond W. Simmonds
Phys. Rev. Lett., arXiv:1307.2630	Amplification limit of weak measurement	Shengshi Pang, **T.A. Brun**, Shengjun Wu and Zeng-Bing Chen
Phys. Rev. Lett.	Coherent Feedback that Beats All Measurement-based Feedback Protocols	**K. Jacobs** and X. Wang
Phys. Rev. Lett.	Simulating many-body Lattice Systems on a Single Nano-mechanical Resonator	K. Jacobs
Phys. Rev. Lett.	Dynamic Dimensionality Identification for Quantum Control	J. Roslund and **H. Rabitz**
IEEE Trans. Auto. Control	Symmetries on Spin Chains: Limited Controllability and Minimal Controls for Full Controllability	Xiaoting Wang (**K. Jacobs** group), Daniel Burgarth, Sophie Schirmer
Phys. Rev. A, arXiv:1210.5538	Optimized Dynamical Decoupling via Genetic Algorithms	G. Quiroz and **D.A. Lidar**
Phys. Rev. X, arXiv:0912.4052	Markovian relaxation and eigenstate-thermalization from an exact simulation of a finite bath	Luciano Silvestri, **K. Jacobs**, Vanja Dunjko, Maxim Olshanii
Adv. Chem. Phys., arXiv:1208.5791	Review of Decoherence Free Subspaces, Noiseless Subsystems, and Dynamical Decoupling	D.A. Lidar
Phys. Rev. A, arXiv:1301.3235	Robust control of quantum gates via sequential convex programming	**R.L. Kosut**, Matthew D. Grace, Constantin Brif
New J. Phys., arXiv:1307.3931	MAX 2-SAT With Up to 108 Qubits	S. Santra, G. Quiroz, G. Ver Steeg, and **D.A. Lidar**
New J. Phys., arXiv:1212.6589	Fluctuation theorems for quantum processes	T. Albash, **D.A. Lidar**, M. Marvian, **P. Zanardi**
arXiv:1306.6934	Universal time-fluctuations in near-critical out-of-equilibrium quantum dynamics	L. Campos Venuti, P. Zanardi
arXiv:1304.7618	On the size of linear superpositions in molecular nanomagnets	F. Troiani, **P. Zanardi**
arXiv:1305.4527	Quantum information-geometry of dissipative quantum phase transitions	L. Banchi, P. Giorda, **P. Zanardi**
arXiv:1303.2832	Local random quantum circuits: ensemble CP maps and swap algebras	P. Zanardi
ECC 2013	Algebraic Conditions for Indirect Controllability in Quantum Coherent Feedback Schemes	F. Albertini and **D. D'Alessandro**

Publications: summary

Nature	Nature Phys.	Nature Comm.	Nature Sci. Rep.
3	1	1	2
Phys. Rev. Lett.	Phys. Rev. A-E	IEEE Trans Auto. Control	New J. Phys.
6	17	2	4
J. Phys. A: Math. Gen.	Quantum Info. Proc.	Math. Control Signals Syst.	J. Math. Phys.
4	1	1	1
Phys. Lett. A	J. Stat. Mech.	Int. J. Mod. Phys. B	J. Chem. Phys.
1	1	1	1
Automatica	Systems & Control Lett.	J. Phys.: Conf. Ser.	book chapters
1	1	1	1
Proc. Les Houches Summer School	Proc. Conf. on Decision and Control	Found. of Phys.	ISCCSP
1	3	1	1

Total published:	57
Total submitted:	17

Breakthroughs – sample highlights

- **Quantum computation in spite of, and in the presence of decoherence**

LETTER

doi:10.1038/nature11505

Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback

R. Vijay[1], C. Macklin[1], D. H. Slichter[1]†, S. J. Weber[1], K. W. Murch[1], R. Naik[1], A. N. Korotkov[2] & I. Siddiqi[1]

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Decoherence-protected quantum gates for a hybrid solid-state spin register

T. van der Sar[1], Z. H. Wang[2], M. S. Blok[1], H. Bernien[1], T. H. Taminiau[1], D. M. Toyli[3], D. A. Lidar[4], D. D. Awschalom[3], R. Hanson[1] & V. V. Dobrovitski[2]

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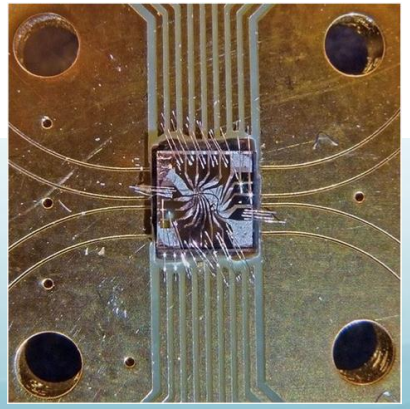
30. This New Quantum Computer Really Sparkles

By Adam Piore | Friday, January 18, 2013



Potential Breakthroughs – sample highlights

Quantum annealing as an old/new paradigm enabling speedups in quantum information processing?

nature COMMUNICATIONS

ARTICLE

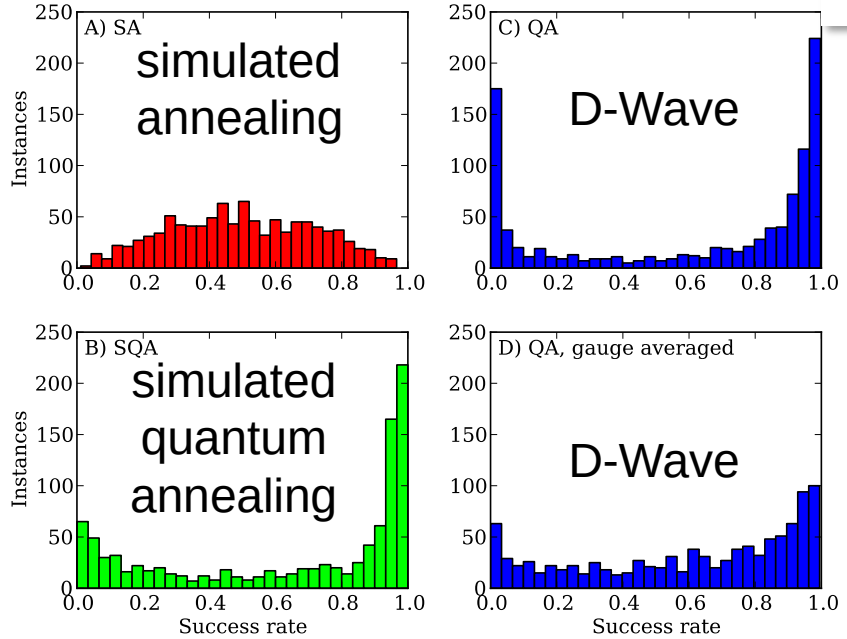
Received 11 Dec 2012 | Accepted 27 May 2013 | Published 28 Jun 2013

DOI: 10.1038/ncomms3067

Experimental signature of programmable quantum annealing

Sergio Boixo[1,2,3], Tameem Albash[3,4], Federico M. Spedalieri[1,3], Nicholas Chancellor[4] & Daniel A. Lidar[2,3,4,5]

arXiv:1304.4595



- D-Wave device: **Quantumness** demonstrated

- **Speedup** remains to be seen

Potential Breakthroughs

Key steps toward advancing central MURI goals:

Develop the theory required to analyze and enable control of open quantum systems

Experimentally demonstrate and verify control of open quantum systems