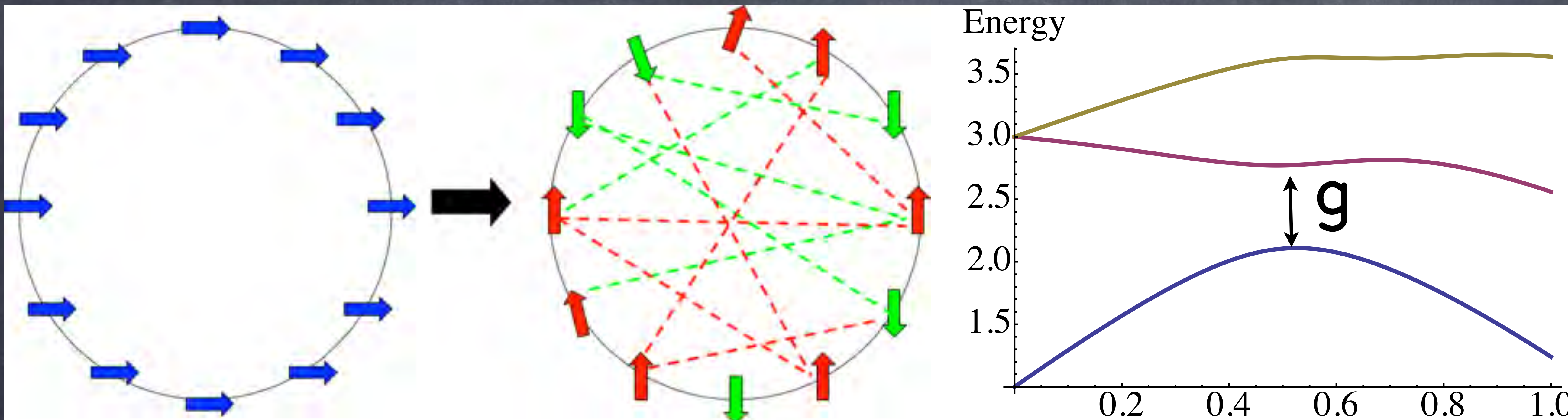
Testing Adiabatic Quantum Computers Using Simple Quantum Simulation

Peter Love
Tufts University

The Adiabatic Model



$$H_i = g\sum_i X_i \rightarrow (1-s)H_i + sH_f \rightarrow H_f = \sum_{\langle i,j\rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i$$

$$T \gg \max_s \frac{|\langle 1; s|\, \dot{H}(s)\, |0; s\rangle\,|}{g^2}$$

Quantum Computation by Adiabatic Evolution, Edward Farhi, Jeffrey Goldstone, Sam Gutmann, Michael Sipser, quant-ph/0001106v1


1903

1964

2016


1903
1964
2016
Classical Computing


1903
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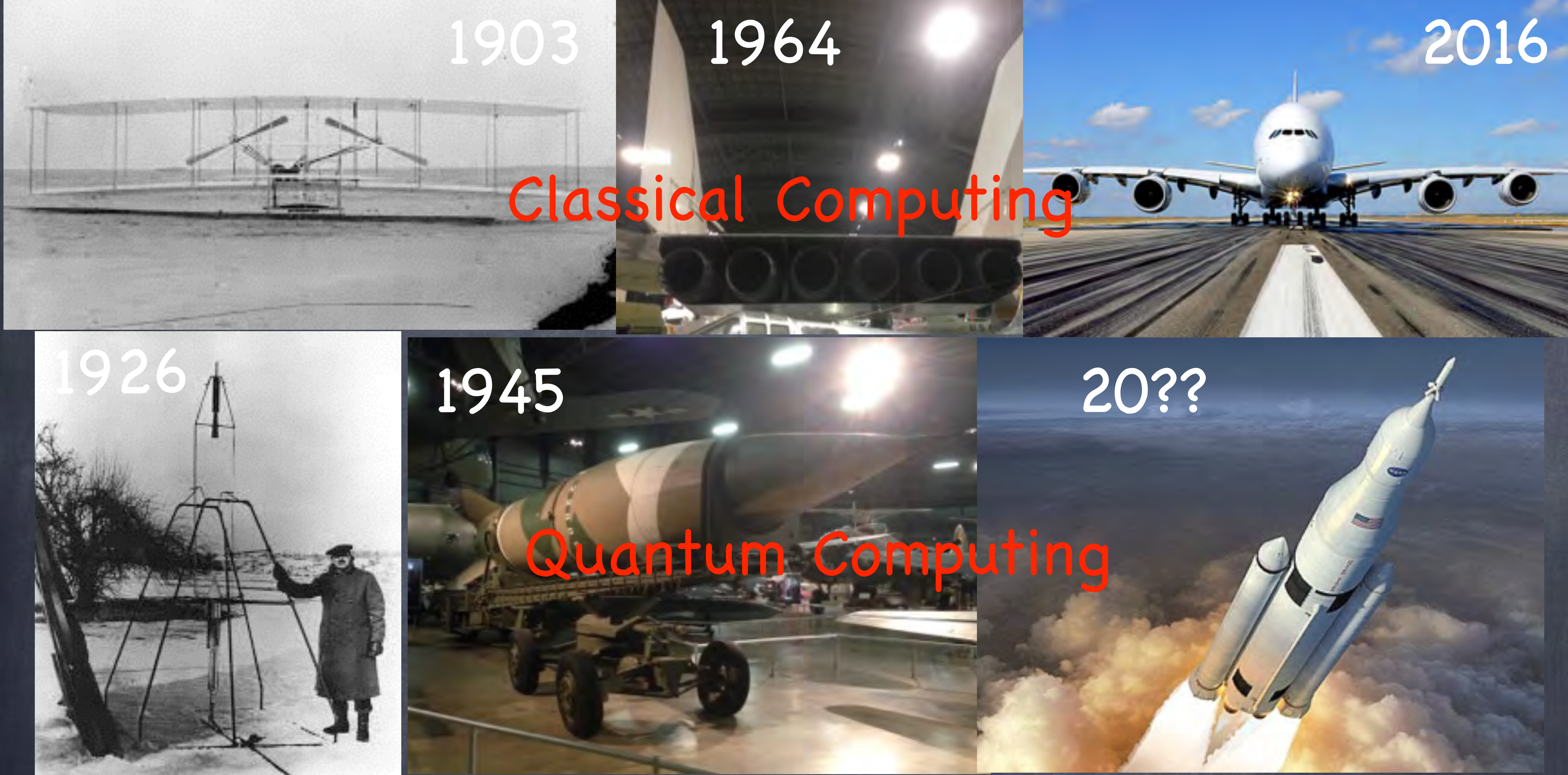
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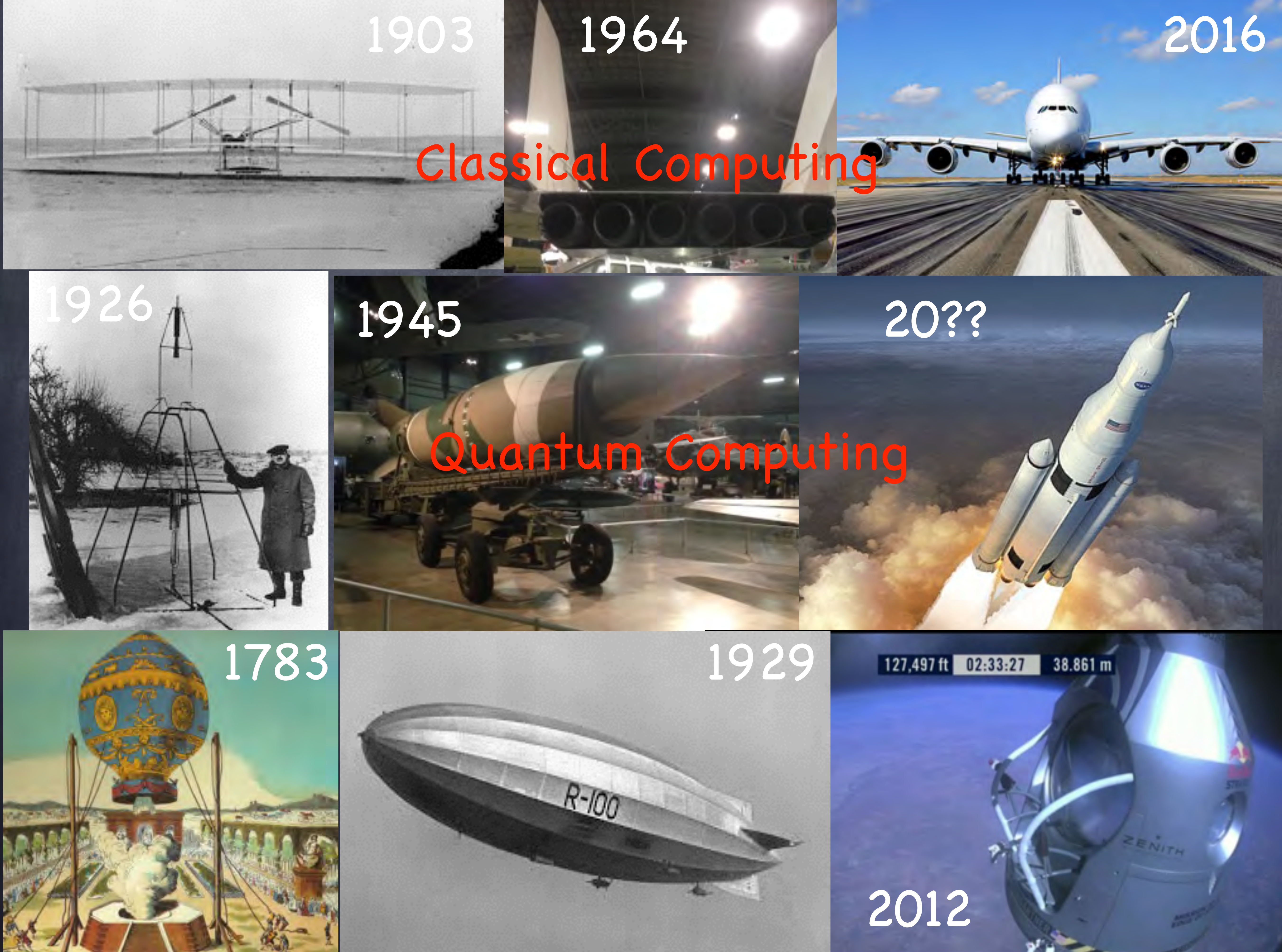
Quantum Computing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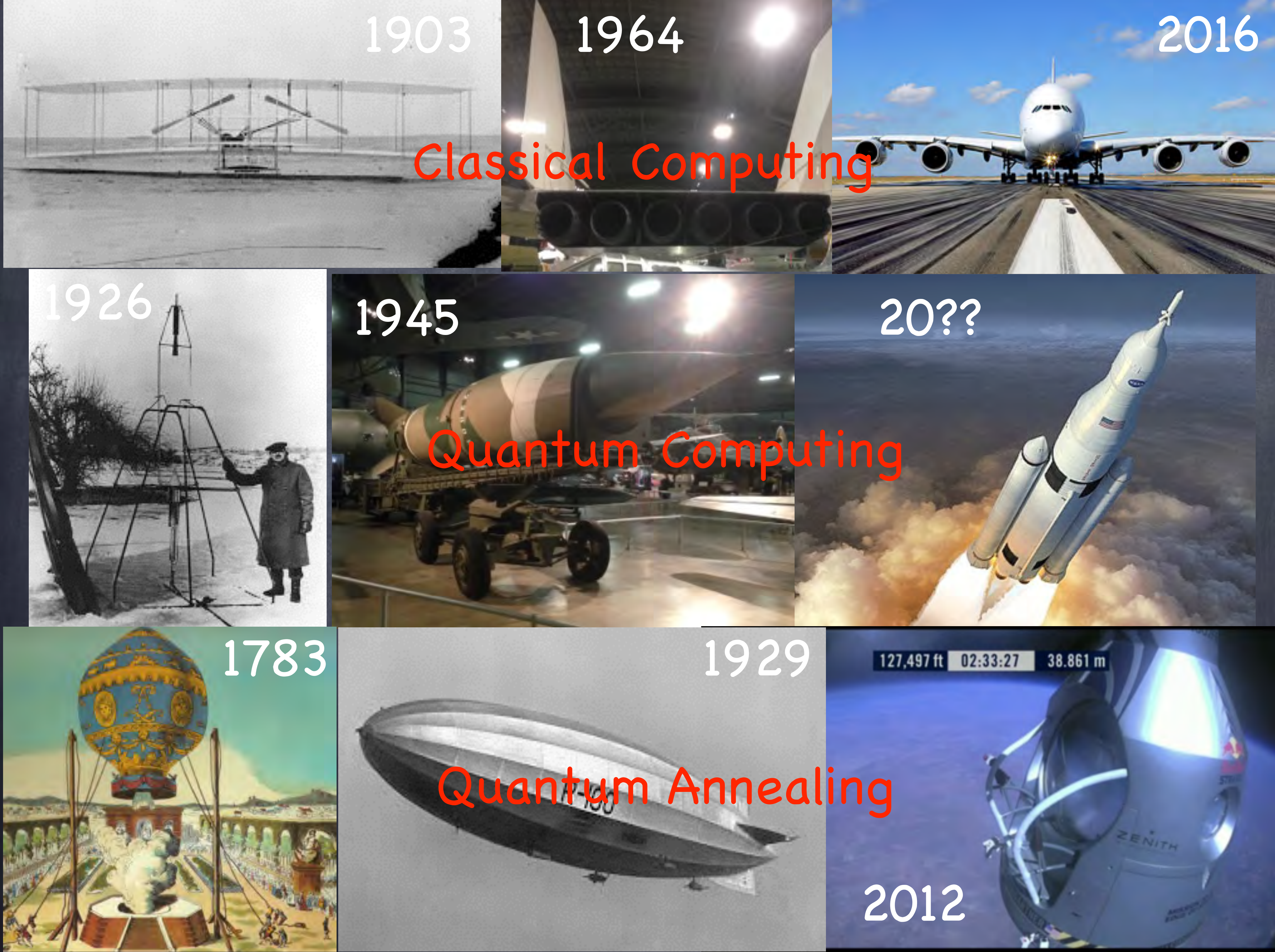
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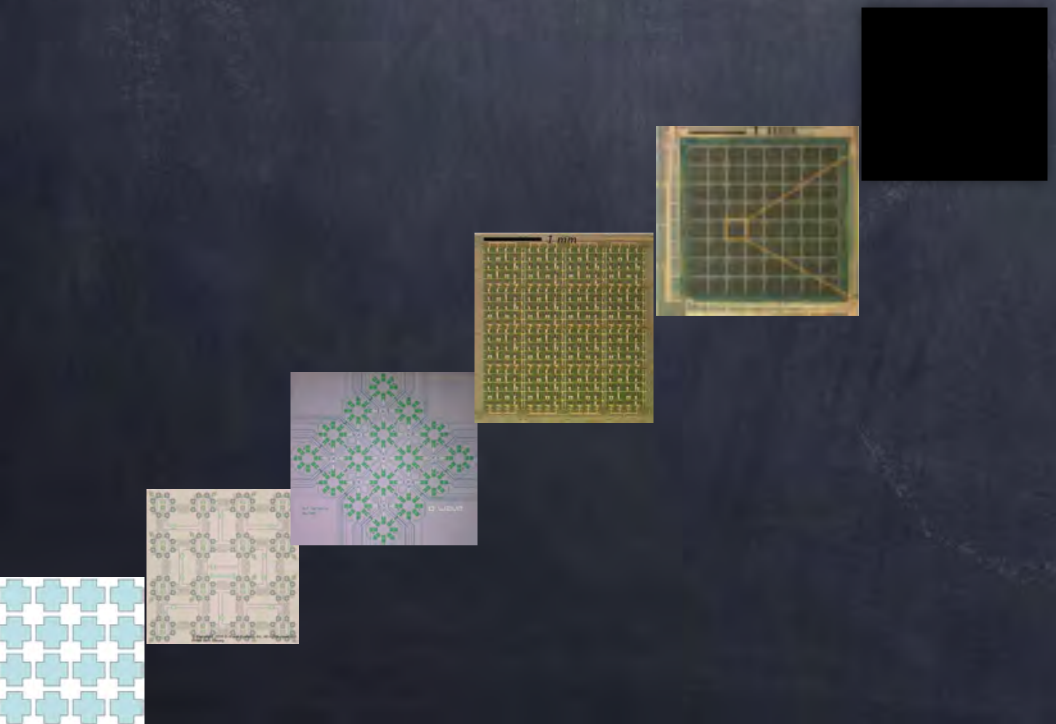
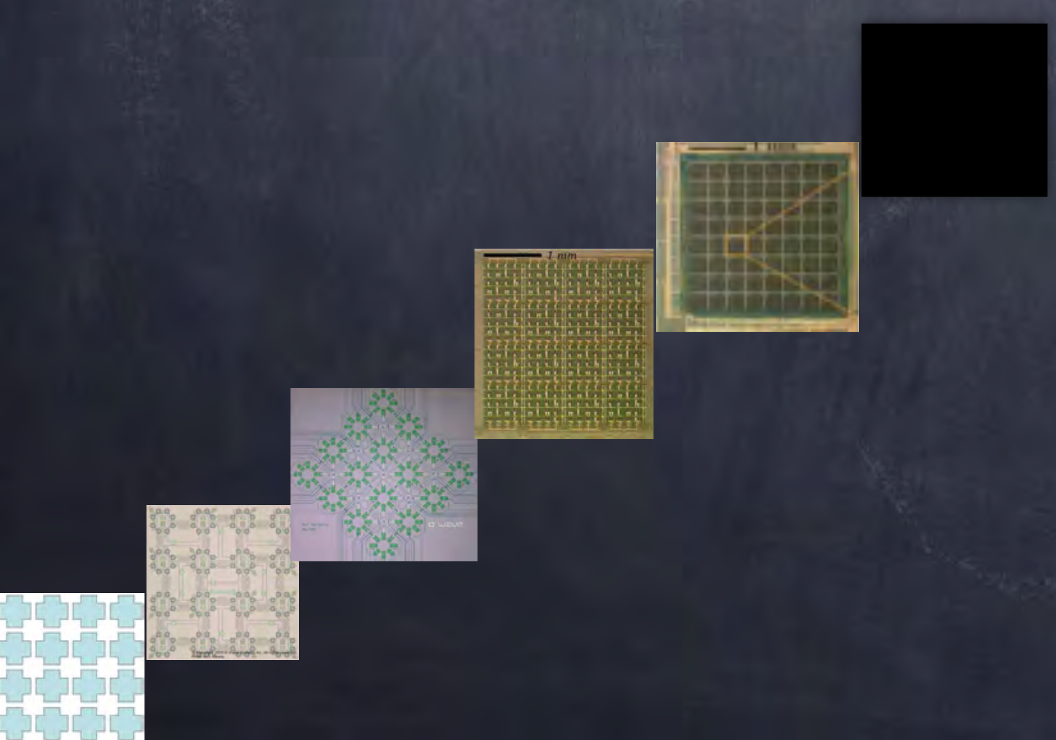


Is there a distant future
for quantum annealers?
What's the first step?

Full QC



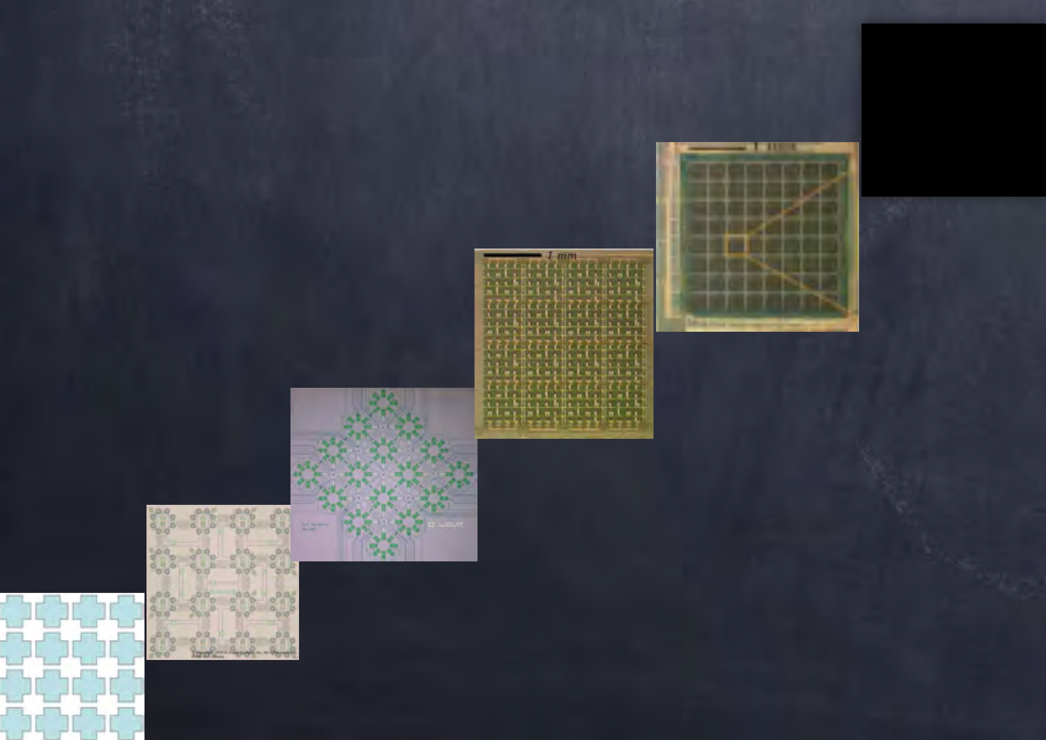
Is there a distant future for quantum annealers?
What's the first step?

Full QC

NorthLock
Goog
IntelBM
SoftWave

Universal AQC

Post-Annealing
Modifications



Is there a distant future for quantum annealers?
What's the first step?

Universal AQC

How do we simulate time evolution in a ground state?

Universal AQC

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$$|0\rangle|0\rangle \rightarrow |\psi_{t=1}\rangle|\psi_{t=2}\rangle$$

Universal AQC

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Universal AQC

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$$\sout{|0\rangle|0\rangle \rightarrow |\psi_{t=1}\rangle|\psi_{t=2}\rangle}$$

Forbidden by no-cloning

Universal AQC

How do we simulate time evolution in a ground state?

$$|0\rangle|0\rangle \rightarrow |\psi_{t=1}\rangle|\psi_{t=2}\rangle$$

Forbidden by no-cloning

Ground state is History state

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} \left(\prod_{i=0}^{t} U_t \right) |\psi_{init}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} |\psi(t)\rangle \otimes |t\rangle$$

Universal AQC

How do we simulate time evolution in a ground state?

Ground state is History state

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} |\psi(t)\rangle \otimes |t\rangle$$

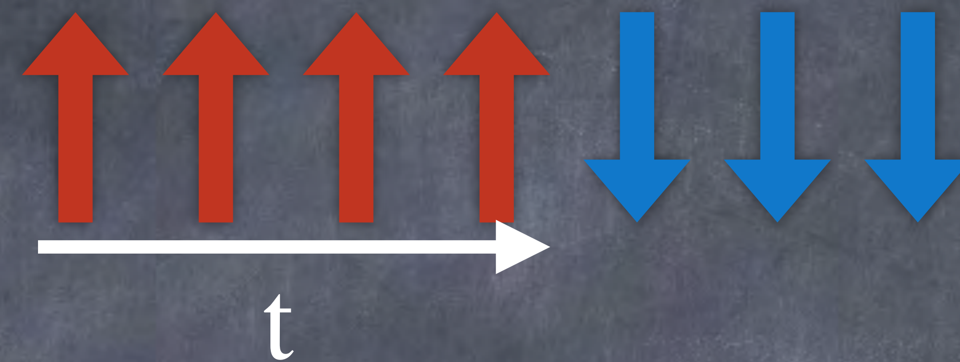
System state

Clock state

Probability to observe $|\psi_T\rangle \otimes |T\rangle$ is $1/(T+1)$

Universal AQC - the clock construction

Clock Register



Logical register

$$H = H_{clock} + H_{init} + \sum_{t=0}^{T} (1-U_t)\otimes|t+1\rangle\langle t| + (1-U_t)^{\dagger}\otimes|t\rangle\langle t+1|$$

Clock Hamiltonian

Initialization Hamiltonian

Propagation Hamiltonian

Universal AQC - gap

$$H = H_{clock} + H_{init} + \sum_{t=0}^{T} (1-U_t)\otimes|t+1\rangle\langle t| + (1-U_t)^\dagger \otimes |t\rangle\langle t+1|$$

Apply change of basis:

$$W = \sum_{j=0}^{T} U_j \ldots U_0 \otimes |j\rangle\langle j|$$

Hamiltonian becomes independent of circuit:

$$H = -\frac{1}{2}\begin{pmatrix} -1 & 1 & 0 & 0 & 0 & \cdots \\ 1 & -2 & 1 & 0 & 0 & \cdots \\ 0 & 1 & -2 & 1 & 0 & \cdots \\ \vdots & 0 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \vdots & 0 & \ddots & \ddots & \ddots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots \end{pmatrix} = D\left[-\frac{1}{2}\frac{d^2}{dx^2}\right]$$

Gap goes like $1/T^2$

Desiderata

Gap scaling - $1/T^2$ implies many repetitions, or requires a quadratic Moore's Lawfor refrigerators, or quadratically increasing connectivity. Need gadgets to increase norm

Types of Coupling - build XZ or XX and ZZ, or build multiple types of coupling. With fixed coupling types need gadgets.

Locality: clock constructions vary from 5-local to 2-local

Complexity proofs: polynomial scaling of Hamiltonian norm is OK
Buildable devices: fixed coupling strength and connectivity.

Biamonte, J. D. & Love, P. J. Realizable Hamiltonians for universal adiabatic quantum computers. Phys Rev A 78, 012352 (2008).

Universal Quantum Computation with a Time-Independent Hamiltonian

New J. Phys. **18** (2016) 023042 doi:10.1088/1367-2630/18/2/023042

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PAPER

Adiabatic and Hamiltonian computing on a 2D lattice with simple two-qubit interactions

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Keywords: quantum computing, Hamiltonian quantum computing, superconducting quantum computing

Abstract

We show how to perform universal Hamiltonian and adiabatic computing using a time-independent Hamiltonian on a 2D grid describing a system of hopping particles which string together and interact to perform the computation. In this construction, the movement of one particle is controlled by the presence or absence of other particles, an effective quantum field effect transistor that allows the construction of controlled-NOT and controlled-rotation gates. The construction translates into a model for universal quantum computation with time-independent two-qubit ZZ and $XX+YY$ interactions on an (almost) planar grid. The effective Hamiltonian is arrived at by a single use of first-order perturbation theory avoiding the use of perturbation gadgets. The dynamics and spectral properties of the effective Hamiltonian can be fully determined as it corresponds to a particular realization of a mapping between a quantum circuit and a Hamiltonian called the space–time circuit-to-Hamiltonian construction. Because of the simple interactions required, and because no higher-order perturbation gadgets are employed, our construction is potentially realizable using super-conducting or other solid-state qubits.

Two local Adiabatic QC!

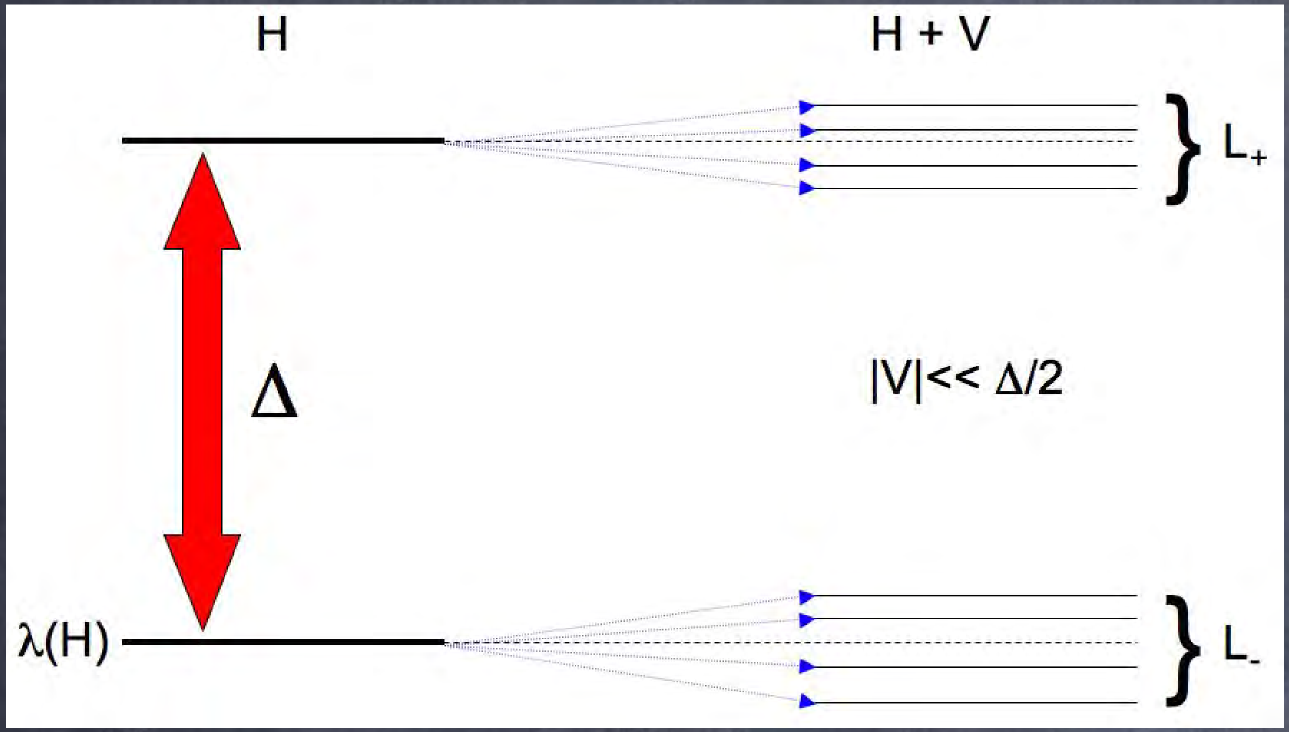
Gap scales as $1/n^3$

Also consider ballistic implementation - no problem with gap

Norman Margolus1990 Parallel quantum computation, Complexity, Entropy,and the Physics of Information, SFI Studies in the Sciences of Complexity (Reading, MA: Addison-Wesley) pp 273–287

Gadgets

Generate k-local interactions in an effective Hamiltonian at kth order in perturbation theory using k-ancilla



$$H_{eff} = V_{-} + \frac{1}{\Delta}\sum_{k=2}^{\infty} V_{+-}\left(\frac{V_{+}}{\Delta}\right)^{k-2} V_{-+}$$

Π_{-} = projector of V onto low energy subspace

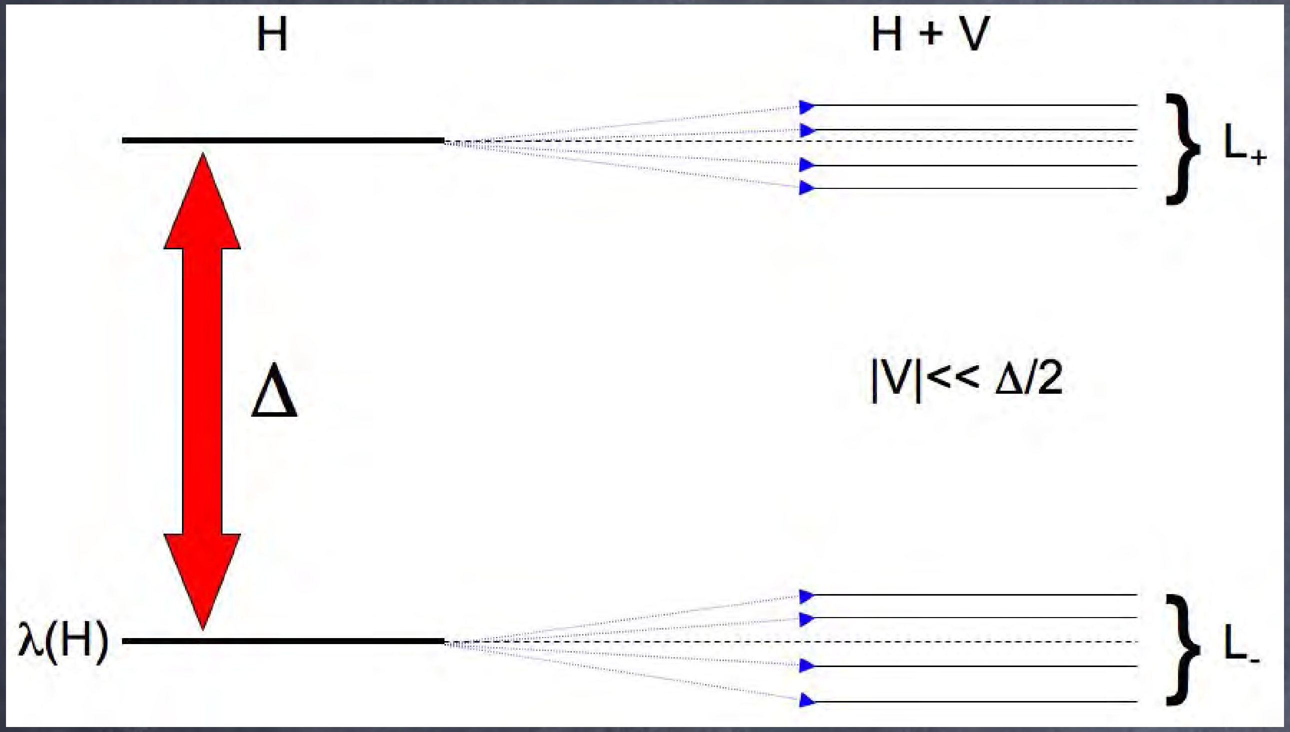
$\Pi_{+} = I - \Pi_{-}$ = projector of V onto low energy subspace

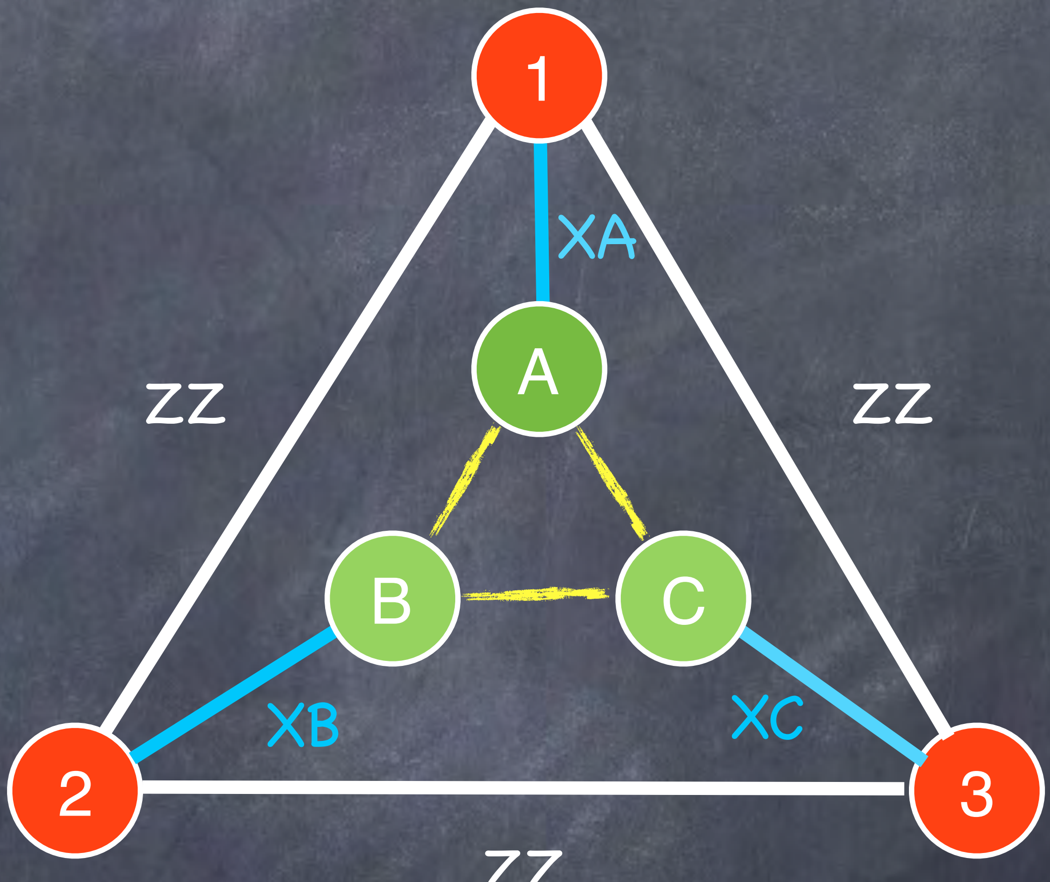
$V_{\pm\mp} = \Pi_{\pm} V \Pi_{\mp}$ = generators of virtual excitations

$V_{\pm\pm} = \Pi_{\pm} V \Pi_{\pm}$ = projections of V

Gadgets

Generate k-local interactions in an effective Hamiltonian at kth order in perturbation theory using k-ancilla





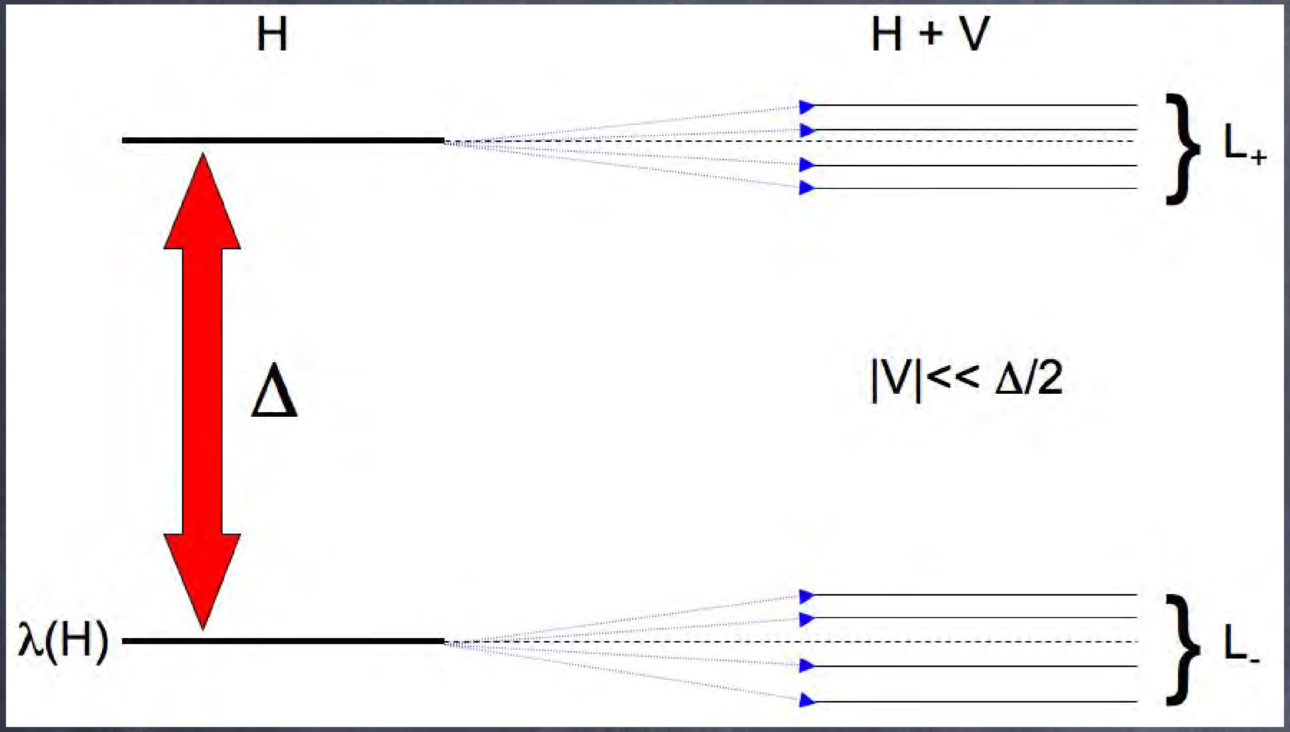
$$V = \left(\frac{\Delta^2}{6}\right)^{1/3} \left(A\otimes X_1 + B\otimes X_2 + C\otimes X_3\right)$$

$$H_{anc} = -\Delta\left(Z_1\otimes Z_2 + Z_1\otimes Z_3 + Z_2\otimes Z_3\right)$$

$$H_T = A\bullet B\bullet C$$

Gadgets

Generate k-local interactions in an effective Hamiltonian at kth order in perturbation theory using k-ancilla

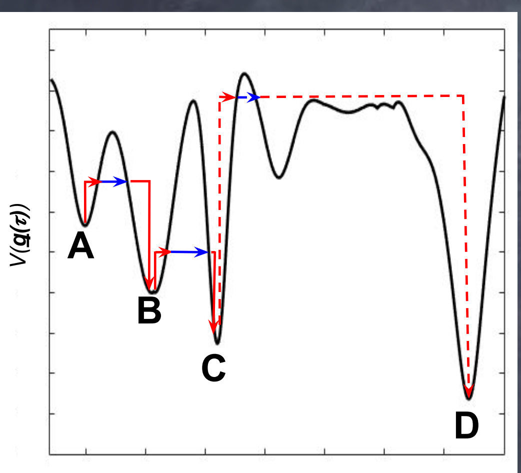


H_{eff} = Old terms + New terms

Flow of parameters

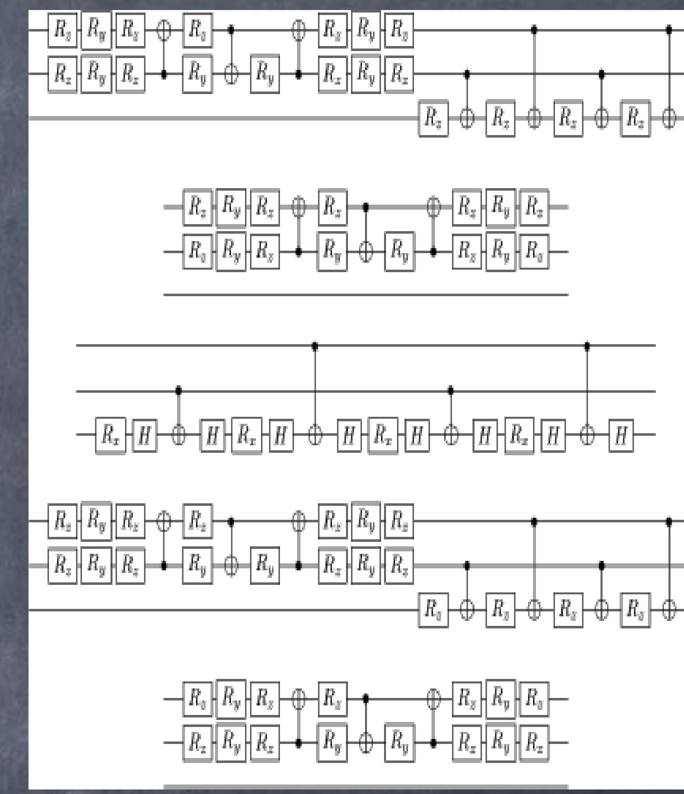
Terms not Physically realizable

Quantum Annealing



Universal AQC

Gate Model



Add XX, Gadgets and clock

Post-Annealing modifications

- Non-stoquastic
- Gadgets (k-local terms)
- Complex interactions (XX)

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Justification for XX

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- Simplest Non-stoquastic term

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- Powers gadgets, simulation, universal AQC

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- Useful for annealing? See Hormozi, Nishimori, Farhi

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- Removes QMC talks from agenda

Post-Annealing modifications

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Justification for XX

- Simplest Non-stoquastic term
- Powers gadgets, simulation, universal AQC
- Useful for annealing? See Hormozi, Nishimori, Farhi
- Removes QMC talks from agenda
- It's what's next!

Stoquastic

- All off-diagonal elements are negative or zero
- (up to simple transformations)

$$H = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i + \Gamma \sum_i X_i$$

Stoquastic

- All off-diagonal elements are negative or zero
- (up to simple transformations)

$$H = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i + \Gamma \sum_i X_i$$

$$Z_k H Z_k = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i + \Gamma \sum_{i \neq k} X_i - \Gamma X_k$$

Stoquastic

- All off-diagonal elements are negative or zero
- (up to simple transformations)

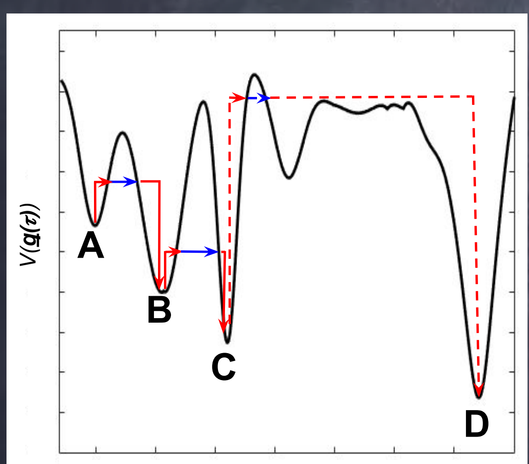
$$H = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i + \Gamma \sum_i X_i$$

$$Z_k H Z_k = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_i h_i Z_i + \Gamma \sum_{i \neq k} X_i - \Gamma X_k$$

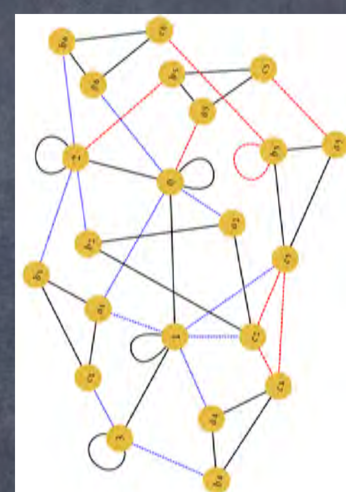
- Simplest non-stoquastic:

$$H = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j + \sum_{\langle ij \rangle} K_{ij} X_i X_j + \sum_i h_i Z_i + \Gamma \sum_i X_i$$

Quantum Annealing

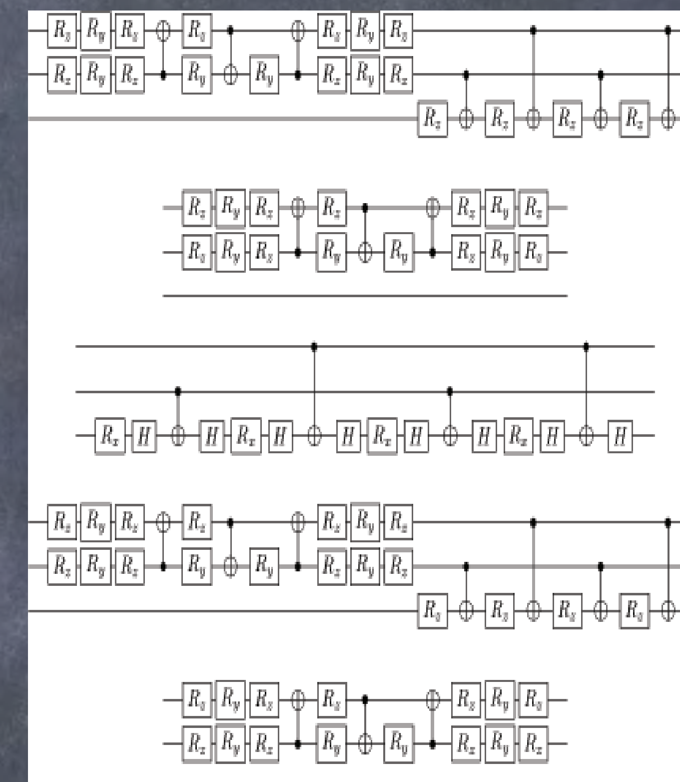


Adiabatic Simulation



Universal AQC

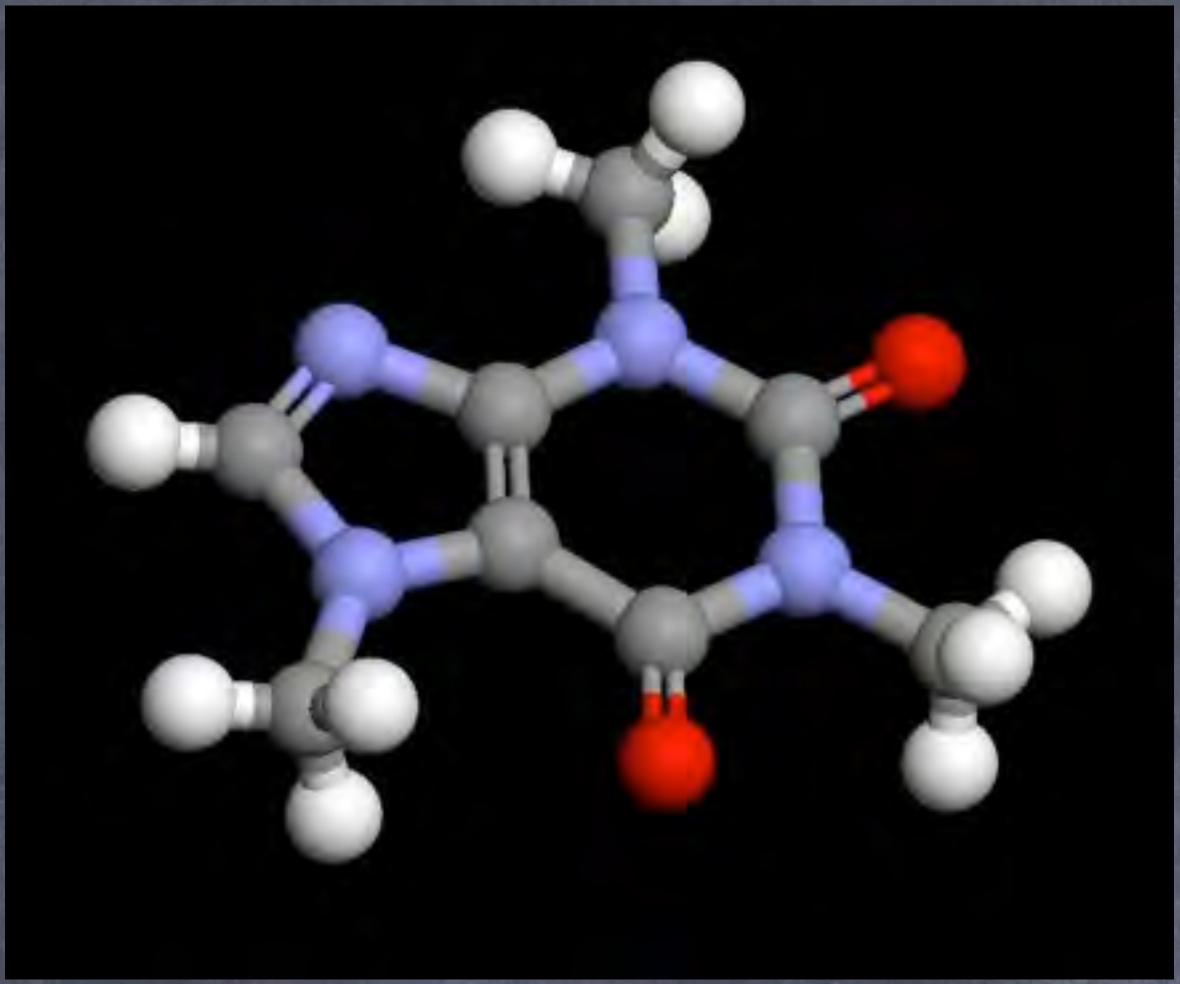
Gate Model



Add XX and Gadgets

Add Clock

Molecular electronic Hamiltonian



$$H = \sum_{i=1}^{n_e} \left(-\frac{\hbar^2}{2m_e} \nabla_i^2 - \sum_{A}^{n_N} \frac{Z_A}{4\pi\varepsilon_0 \left| \vec{r}_i - \vec{R}_A \right|} \right) + \sum_{i<j}^{n_e} \frac{e^2}{4\pi\varepsilon_0 \left| \vec{r}_i - \vec{r}_j \right|}$$

To represent as a qubit problem we must discretize

Discretize in a basis of Molecular orbitals

For each orbital define a_k and $a_k^\dagger$ satisfying:

$$\{a_j, a_k\} = 0 \qquad \{a_j^\dagger, a_k^\dagger\} = 0 \qquad \{a_j, a_k^\dagger\} = \delta_{jk} 1$$

Discretize in a basis of Molecular orbitals

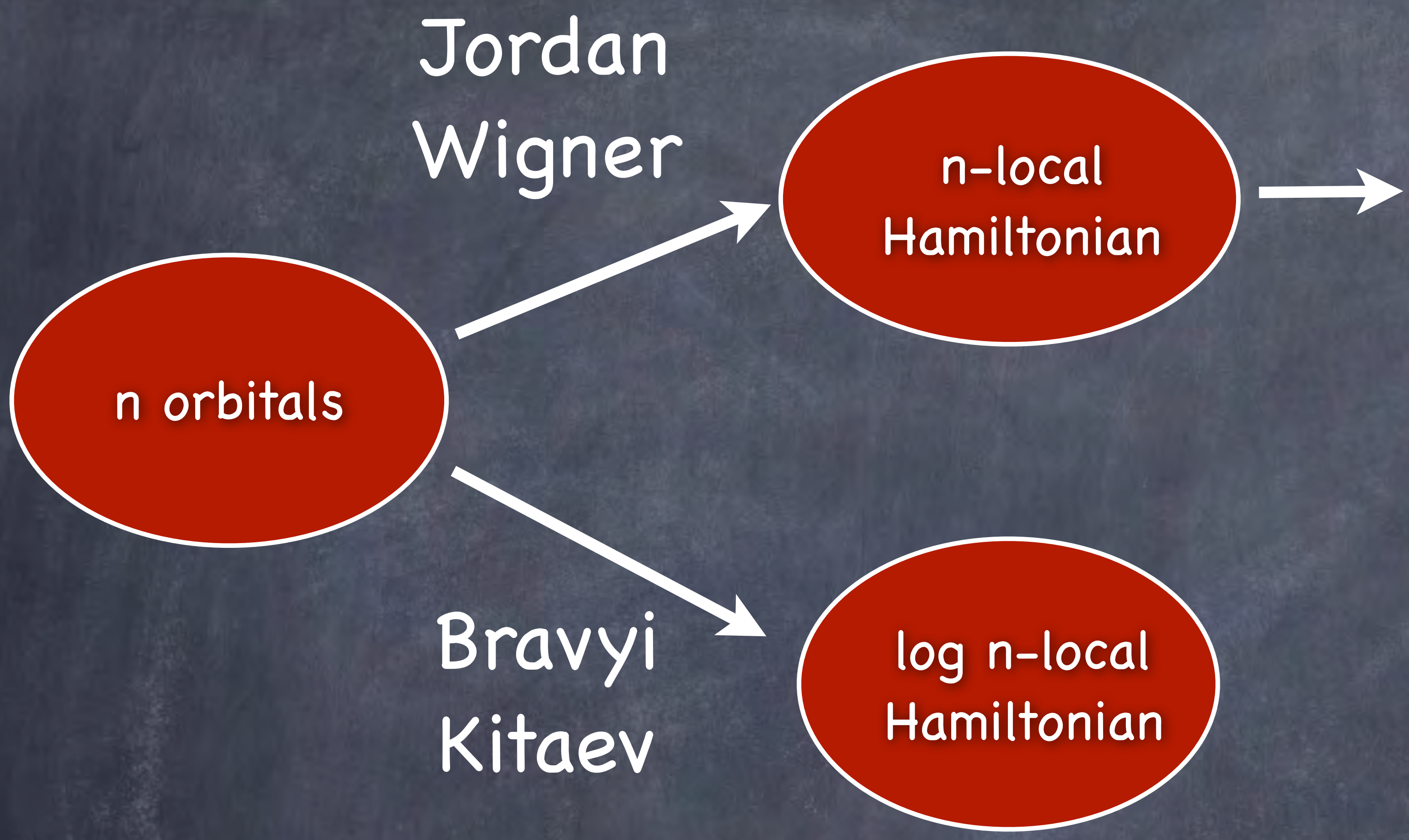
For each orbital define a_k and $a_k^\dagger$ satisfying:

$$\{a_j, a_k\} = 0 \qquad \{a_j^\dagger, a_k^\dagger\} = 0 \qquad \{a_j, a_k^\dagger\} = \delta_{jk} 1$$

Write the second-quantized Hamiltonian:

$$H = \sum_{ij} h_{ij} a_i^\dagger a_j + \sum_{ijkl} h_{ijkl} a_i^\dagger a_j^\dagger a_k a_l$$

Fermionic analog simulator



Couplings scale as

$$\sim \Delta^{n}$$

Not scalable.

Couplings scale as

$$\sim \Delta^{\log n}$$

Scalable.

S. Bravyi and A. Yu. Kitaev, Annals of Physics, **298** 210-226 (2002)
J. T. Seeley, M. Richard, P. J. Love J. Chem. Phys. 137, 224109 (2012),
Adiabatic Quantum Simulation of Quantum Chemistry, Ryan Babbush, Peter J. Love Alan Aspuru-Guzik arXiv:1311.3967, Scientific Reports, 4, 6603, (2014)

What couplings are needed?

$$\alpha Y_i Y_j \rightarrow \underbrace{-\alpha X_i X_j}_{A} \underbrace{Z_i Z_j}_{B}$$

Gadgets reduce locality - they can also reduce the types of interaction to XX, ZZ and XZ

This quantum simulator has the same couplings as a Universal AQC, but not the clock

Intermediate between quantum annealing and Universal AQC

Biamonte, J. D. & Love, P. J. Realizable Hamiltonians for universal adiabatic quantum computers. Phys Rev A 78, 012352 (2008).
Babbush, R., Love, P. J. & Aspuru-Guzik, A. Adiabatic Quantum Simulation of Quantum Chemistry. 1311.3967v2 (2013).

Validation by inefficient simulation of elementary quantum systems

- If we think we will need gadgets and clocks in the future, what could we be doing now to make sure they work?
- Can we display properties of simple single particle QM - superposition, dispersion, energy quantization in an AQC?
- Can we show evidence that superposition states exist in an AQC between logical basis states with widely different hamming weights?

In gate model requirements for validation (tomography) are the same as the requirements for computation

In restricted models of QC validation is a separate problem

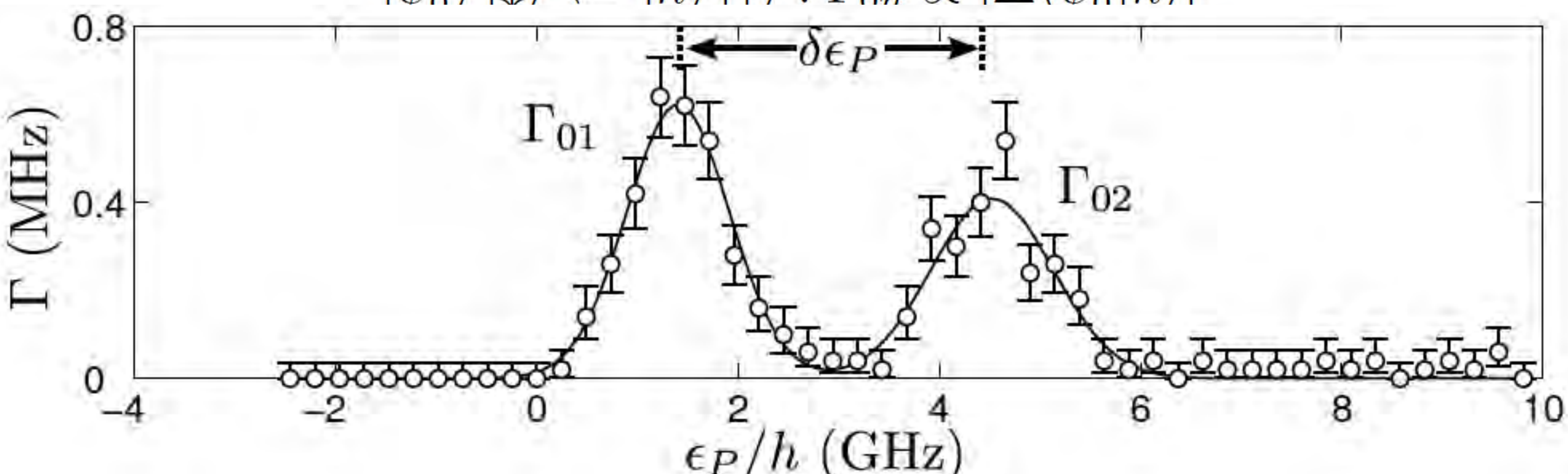
With a hammer, everything looks like….

$$H_P = \frac{\epsilon}{2}(\mathbf{1}_P - Z_P) - \frac{\Delta}{2}X_P = \epsilon \left|\downarrow\right\rangle \left\langle\downarrow\right|_P - \frac{\Delta}{2}X_P$$

$$H_{S+P} = H_S + H_P - JZ_S \otimes (\mathbf{1}_P - Z_P) = H_S + H_P - 2JZ_S \otimes \left|\downarrow\right\rangle \left\langle\downarrow\right|_P$$

$$H_{S+P} = \underbrace{(\epsilon - 2JZ_S + H_S) \otimes \left|\downarrow\right\rangle \left\langle\downarrow\right|_P}_{\mathcal{L}_\downarrow} + \underbrace{H_S \otimes \left|\uparrow\right\rangle \left\langle\uparrow\right|_P}_{\mathcal{L}_\uparrow} - \frac{\Delta}{2}X_P$$

$$\left|\psi_0^\downarrow\right\rangle \left|\downarrow\right\rangle \overset{\Gamma_{0n}}{\rightleftharpoons} \left|n\right\rangle \left|\uparrow\right\rangle : \Gamma_{0n} \propto \left|\Delta \left\langle\psi_0^\downarrow | n\right\rangle\right|^2$$



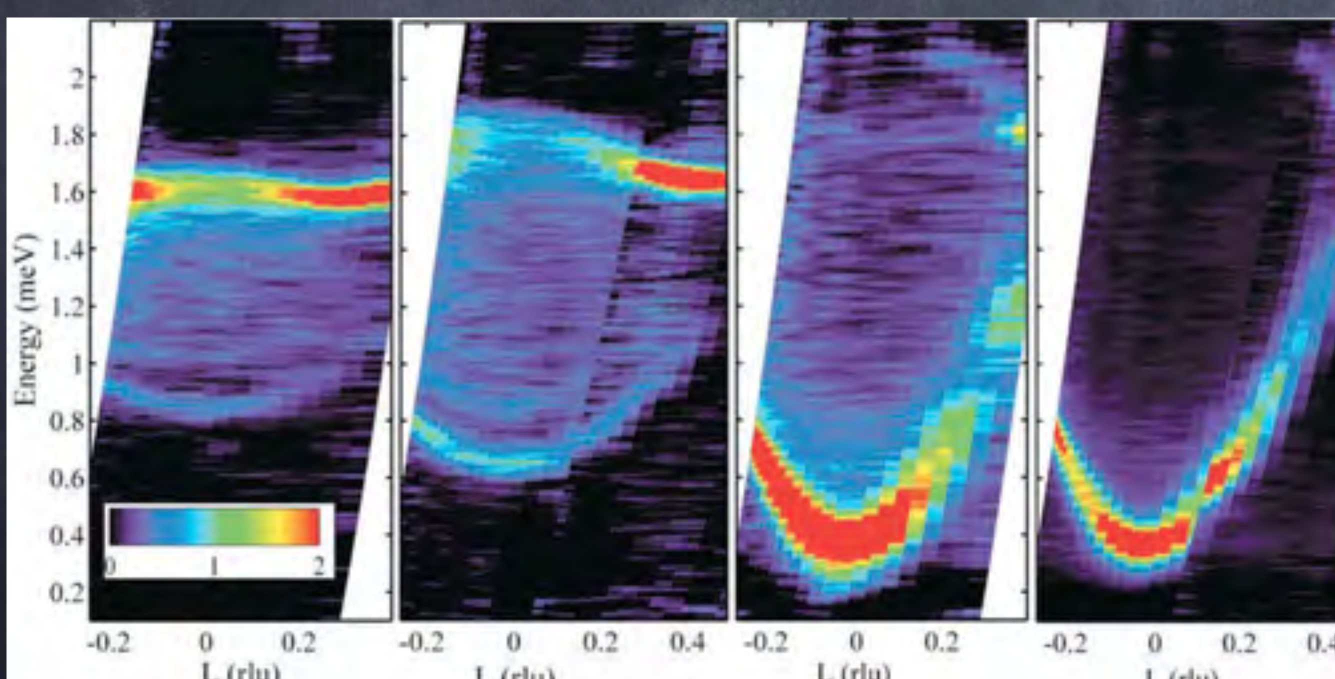
A. J. Berkley, A. J. Przybysz, T. Lanting, R. Harris, N. Dickson, F. Altomare, M. H. Amin, P. Bunyk, C. Enderud, E. Hoskinson, M. W. Johnson, E. Ladizinsky, R. Neufeld, C. Rich, A. Yu. Smirnov, E. Tolkacheva, S. Uchaikin, and A. B. Wilson. Tunneling Spectroscopy Using a Probe Qubit. Physical Review B. **87** 020502 2013.

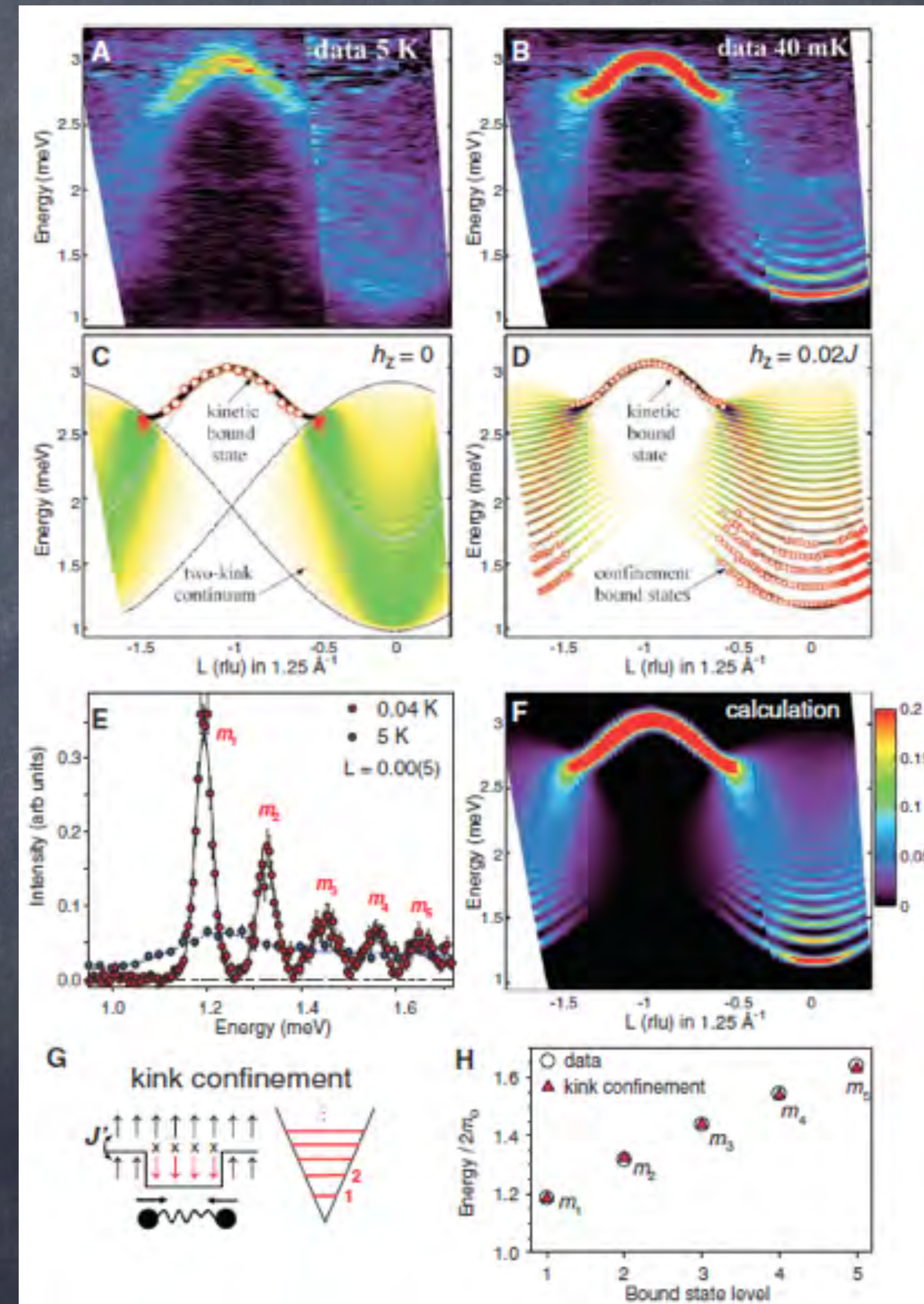
Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E_8 Symmetry

R. Coldea,[1]* D. A. Tennant,[2] E. M. Wheeler,[1]† E. Wawrzynska,[3] D. Prabhakaran,[1]
M. Telling,[4] K. Habicht,[2] P. Smeibidl,[2] K. Kiefer[2]

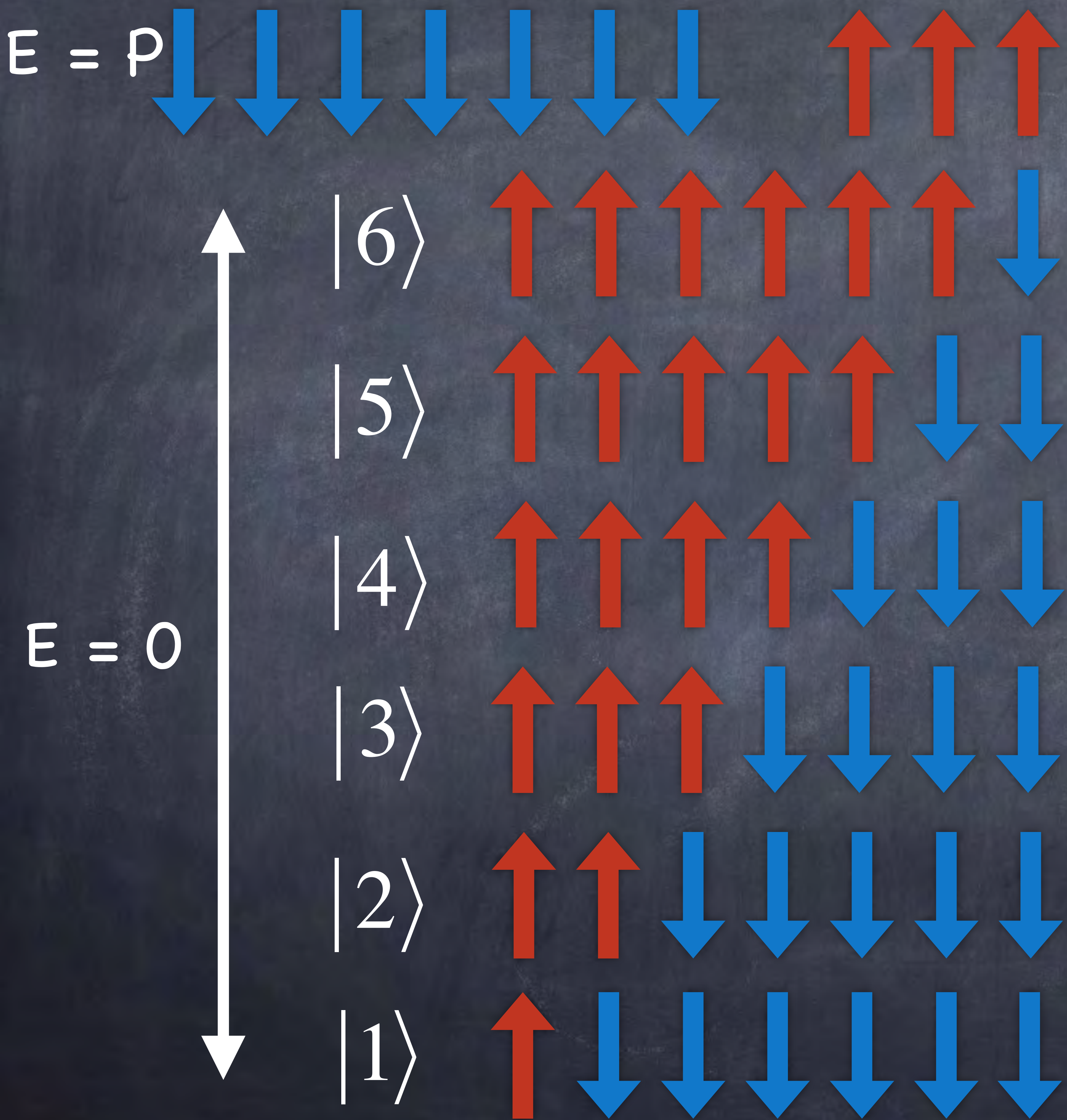
Quantum phase transitions take place between distinct phases of matter at zero temperature. Near the transition point, exotic quantum symmetries can emerge that govern the excitation spectrum of the system. A symmetry described by the E_8 Lie group with a spectrum of eight particles was long predicted to appear near the critical point of an Ising chain. We realize this system experimentally by using strong transverse magnetic fields to tune the quasi–one-dimensional Ising ferromagnet $CoNb_2O_6$ (cobalt niobate) through its critical point. Spin excitations are observed to change character from pairs of kinks in the ordered phase to spin-flips in the paramagnetic phase. Just below the critical field, the spin dynamics shows a fine structure with two sharp modes at low energies, in a ratio that approaches the golden mean predicted for the first two meson particles of the E_8 spectrum. Our results demonstrate the power of symmetry to describe complex quantum behaviors.

SCIENCE VOL 327 (2010) P177





The kink basis - clock states



Ferromagnetic penalty on adjacent pairs

$H_F = J(1 - ZZ)/2$

Boundary penalty

$H_P = P(1 - Z_1)/2 + P(1 - Z_N)/2$

The transverse field in the kink basis

$$\sum_{i=1} X_i |k\rangle$$ = uniform superposition of all states Hamming distance one from $|k\rangle$

Projecting back onto the kink basis:

$$\sum_{i=1} X_i \uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow = \uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow + \uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow$$

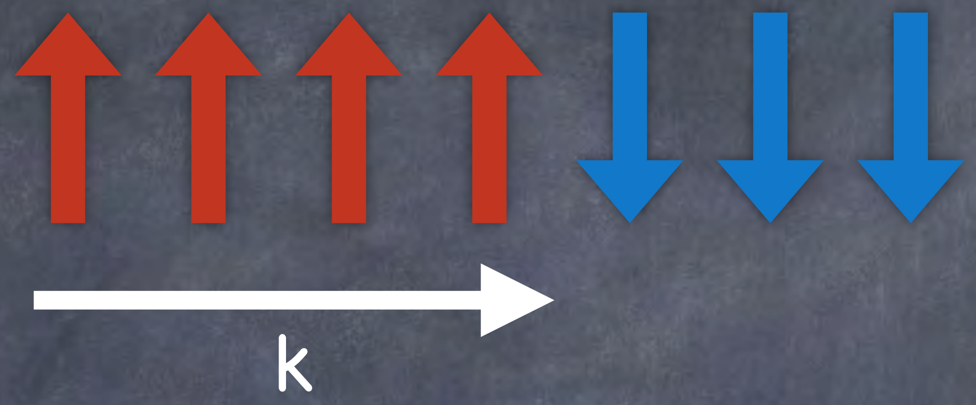
Or:

$$P\left(\sum_{i=1} X_i |k\rangle\right) = |k+1\rangle + |k-1\rangle$$

Can build a 1-D kinetic energy from this:

$$P\left(\frac{1}{L^2}\sum_{i=1} X_i |k\rangle - \frac{1}{L^2}|k\rangle\right) = \frac{|k+1\rangle - 2|k\rangle + |k-1\rangle}{L^2} = D\left[\frac{d^2}{dx^2}\right]$$

The local field in the kink basis



$$\sum_{i=1}^{L} h_i Z_i |k\rangle = \left(\sum_{i=k+1}^{L} h_i - \sum_{i=1}^{k} h_i \right) |k\rangle = \left(\sum_{i=1}^{L} h_i - 2\sum_{i=1}^{k} h_i \right) |k\rangle$$

Can interpret this as a potential, where up to a constant:

$$V(k) = -2\sum_{i=1}^{k} h_i$$

Obvious case: linear potential, constant field, kink confinement.

Polynomial potentials

Find h_i such that

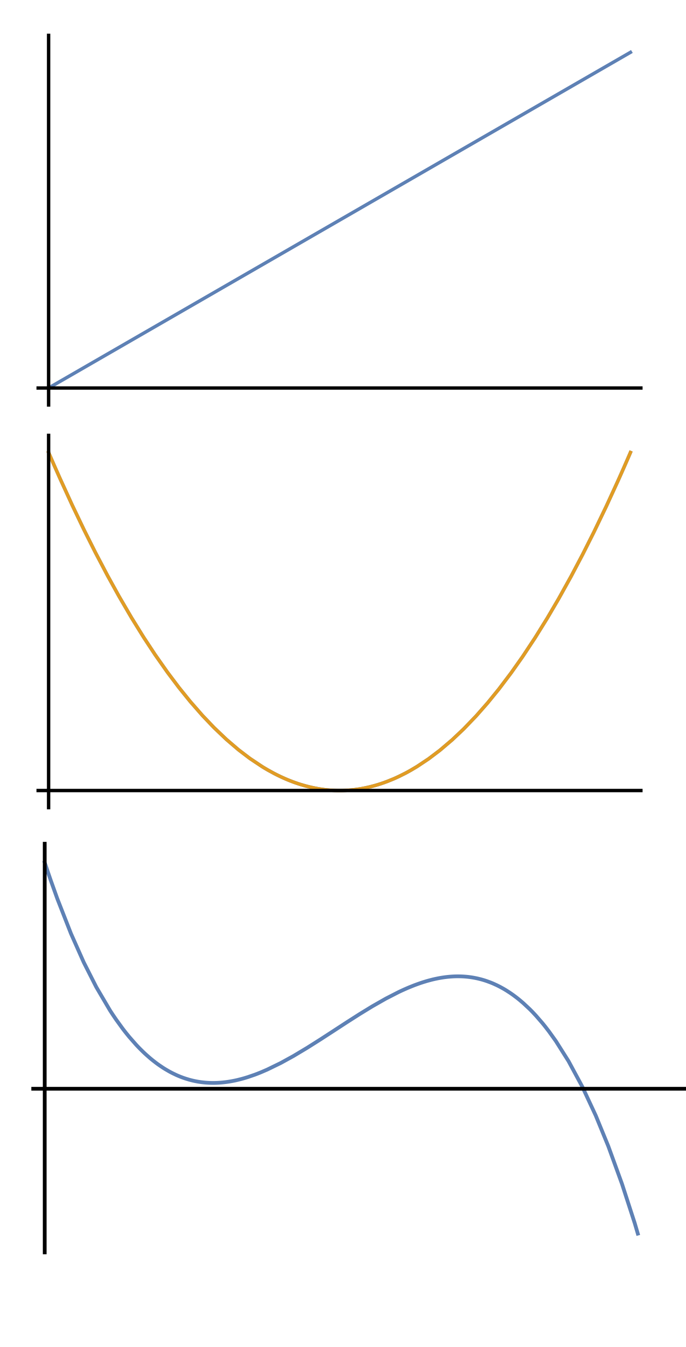
$$V(k) = -2\sum_{i=1}^{k} h_i = k^p$$

Straightforward: use Pascal's Identity:

$$(k+1)^p = 1 + \sum_{l=0}^{p-1} \binom{p}{l} \sum_{i=1}^{k} i^l$$

Up to a constant:

$$h_i = -\frac{1}{2}\sum_{l=0}^{p-1} \binom{p}{l} i^l = \frac{i^p - (1+i)^p}{2}$$



Maximum required local field grows exponentially with polynomial degree - recall the goal here is validation not simulation.

Errors

Discretization error:

$$\lim_{n\to\infty} P(H) = H_{cont}$$

Standard numerical analysis

Leakage error:

$$\lim_{J\to\infty} H = P(H)$$

Gadget analysis tells you corrections to P(H).
These corrections tell you about virtual excitations in your system.

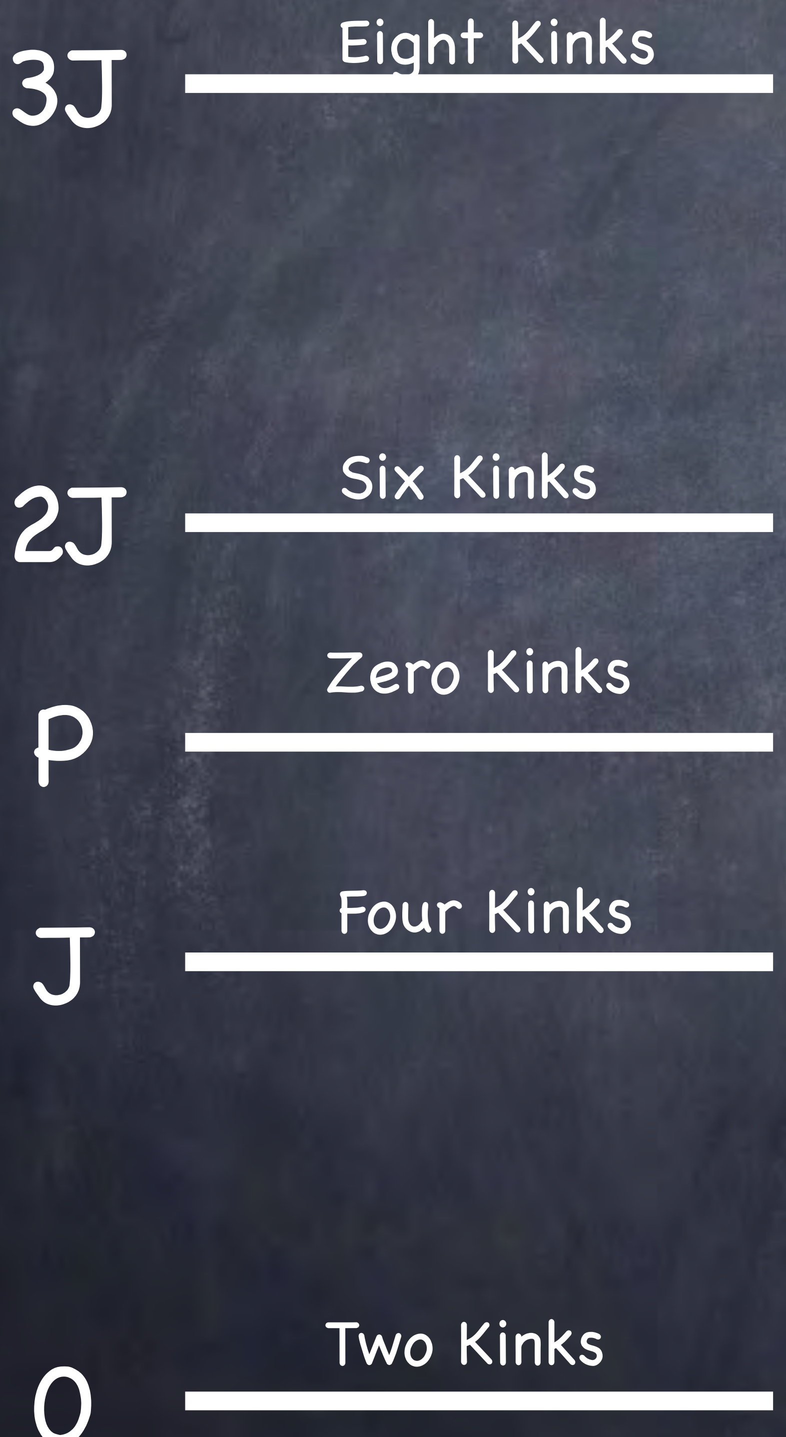
Inefficient elementary simulations are probes of requirements for post-annealing AQC

If simple kink basis simulations work at all then you can make clock states.

Leakage Errors in simple simulations tell you whether Gadgets
will work in your system.

First error can be used to detect XX

Gadgets



$$H_{eff} = P(H) + \sum_{k=2}^{\infty} V_{-+} G_{+} \left(V_{+} G_{+} \right)^{k-2} V_{+-}$$

$$G_{+} = -\sum_{E>0} \sum_{r=1}^{d_E} \frac{|E,r\rangle\langle E,r|}{E}$$

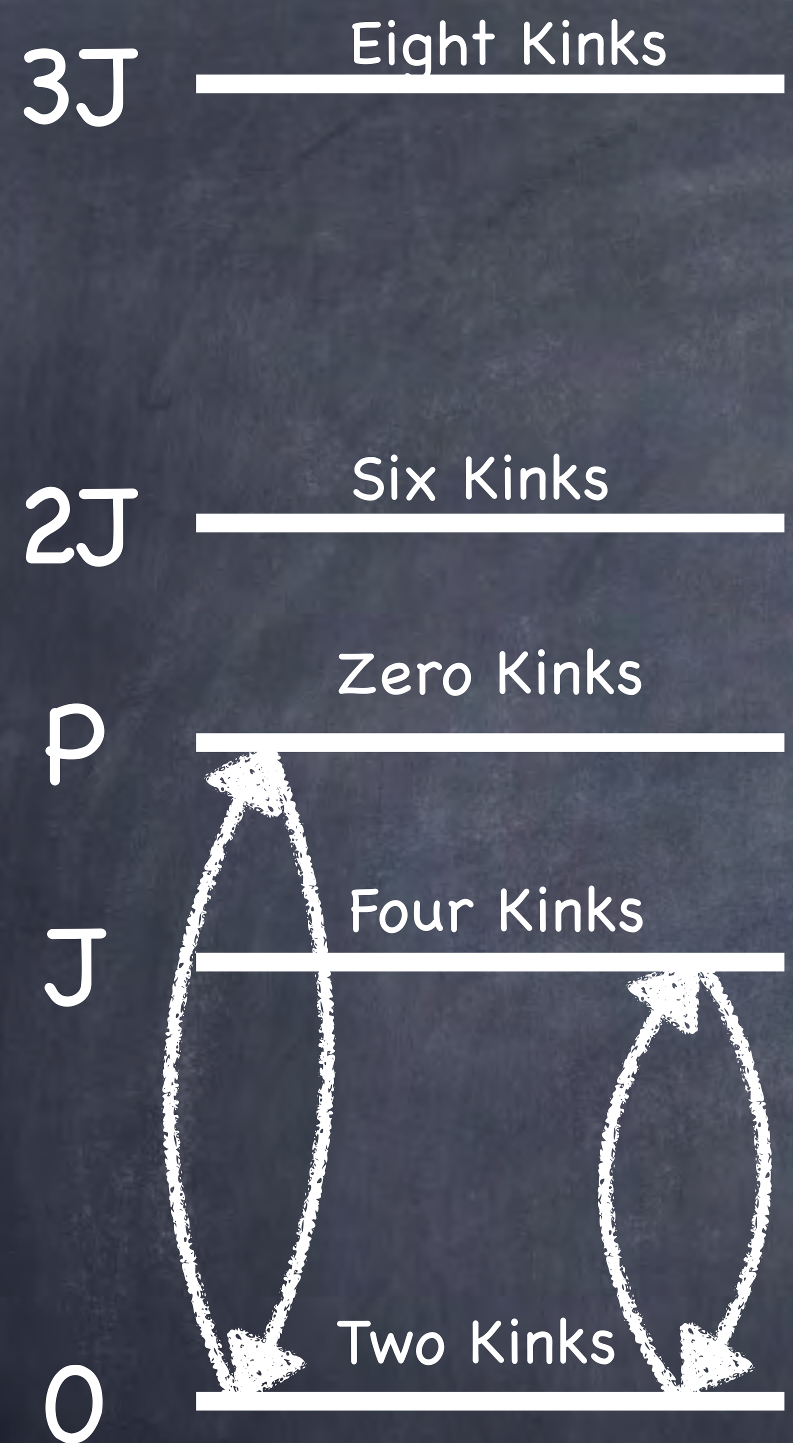
Π_{-} projector onto two kink space

$$\Pi_{+} = \mathrm{I} - \Pi_{-}$$

$$V_{\pm\mp} = \Pi_{\pm} V \Pi_{\mp} \qquad V_{\pm\pm} = \Pi_{\pm} V \Pi_{\pm}$$

Potential is diagonal - doesn't couple states with different numbers of kinks.

Error analysis is same for all potentials.

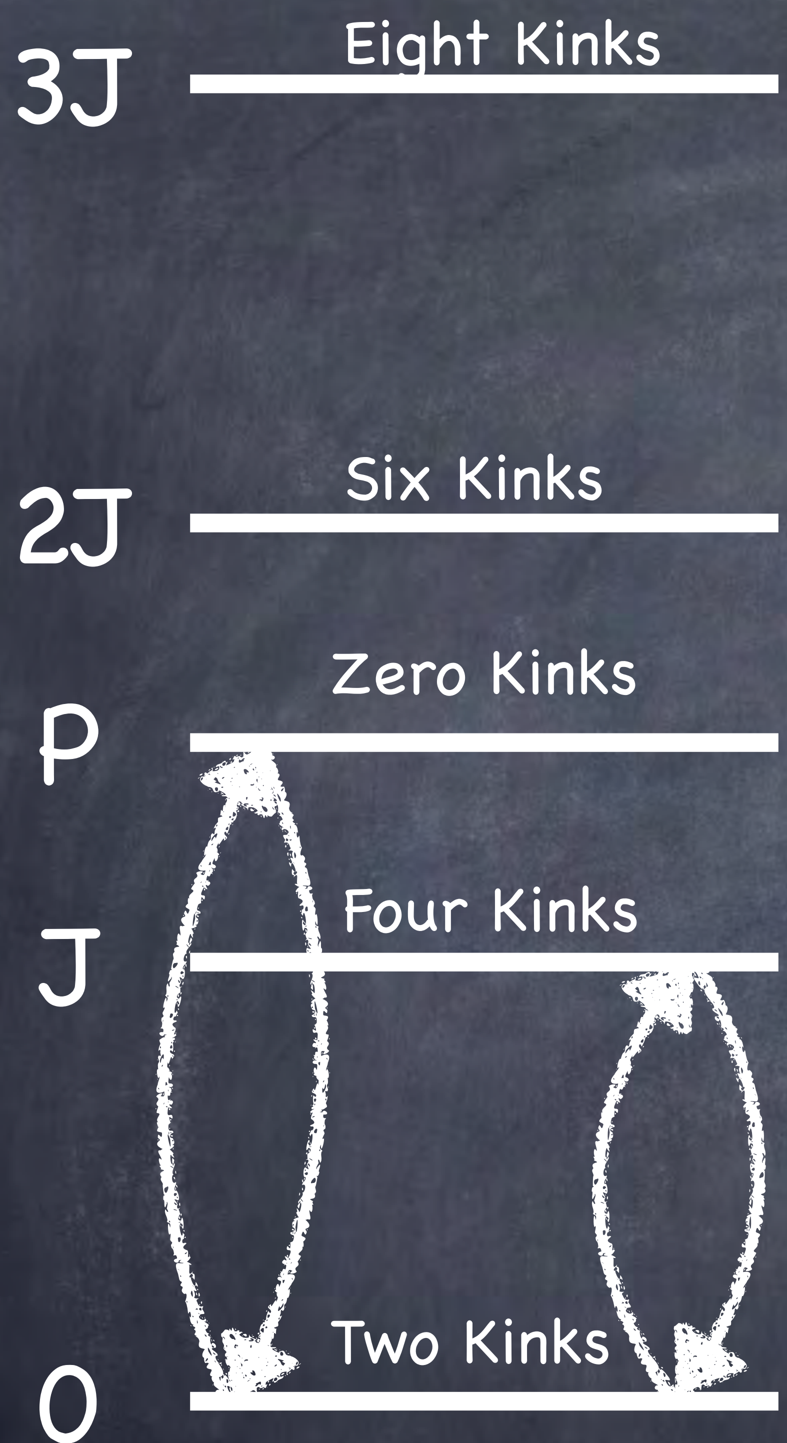


Two kinds of term:

Terms that are already present - flow of coefficients.

Terms that are new. Errors.

$$H_{eff} = P(H) - \frac{\lambda^2 (L-3)}{2J} \mathrm{I} - \frac{3\lambda^2}{4J} \left[|1\rangle\langle 1| + |L\rangle\langle L| \right] - \frac{\lambda^2}{2J} P\left(\sum_{i=1}^{L-1} X_i X_{i+1} \right)$$



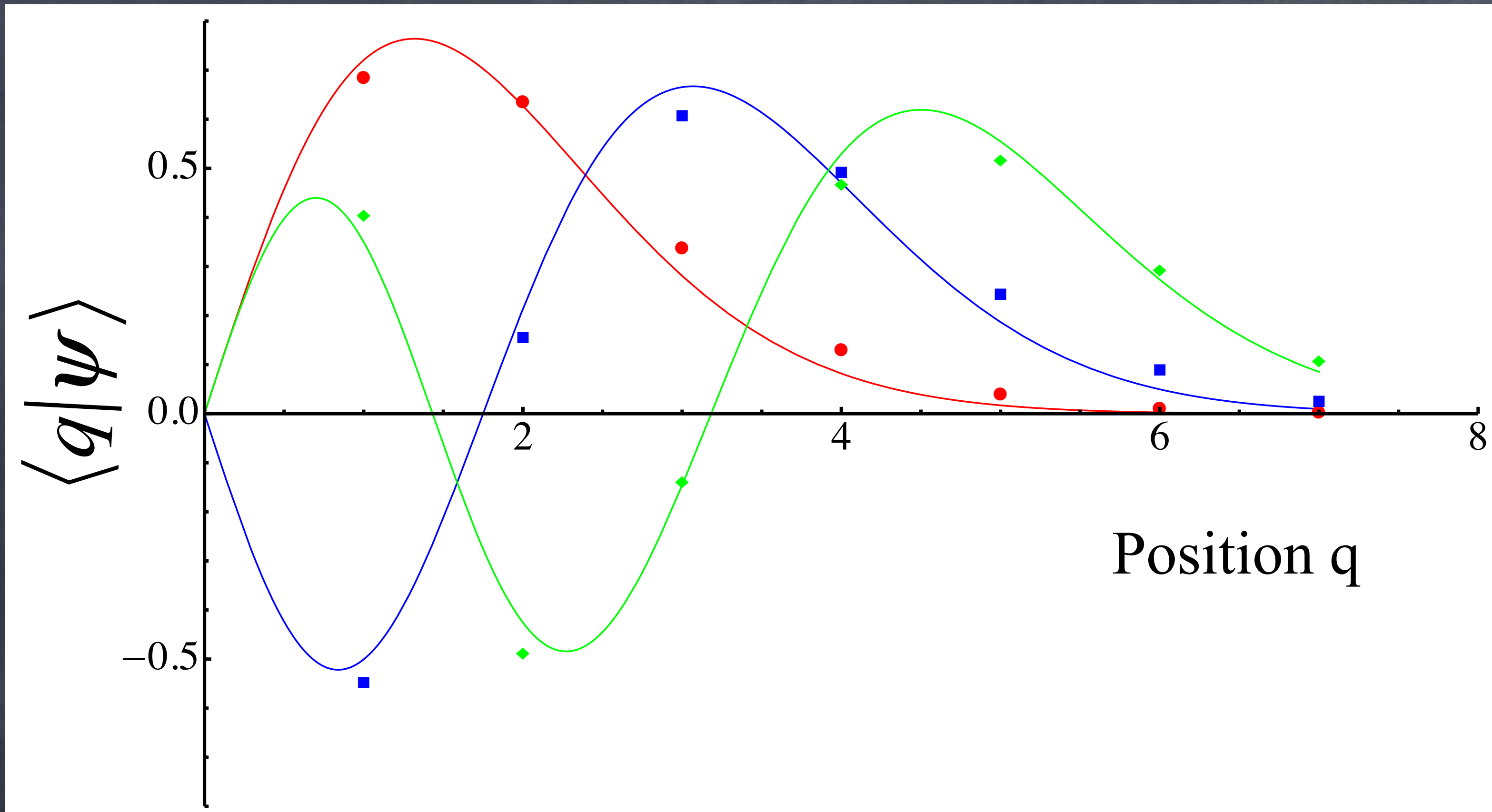
Two kinds of term:

Terms that are already present - flow of coefficients.

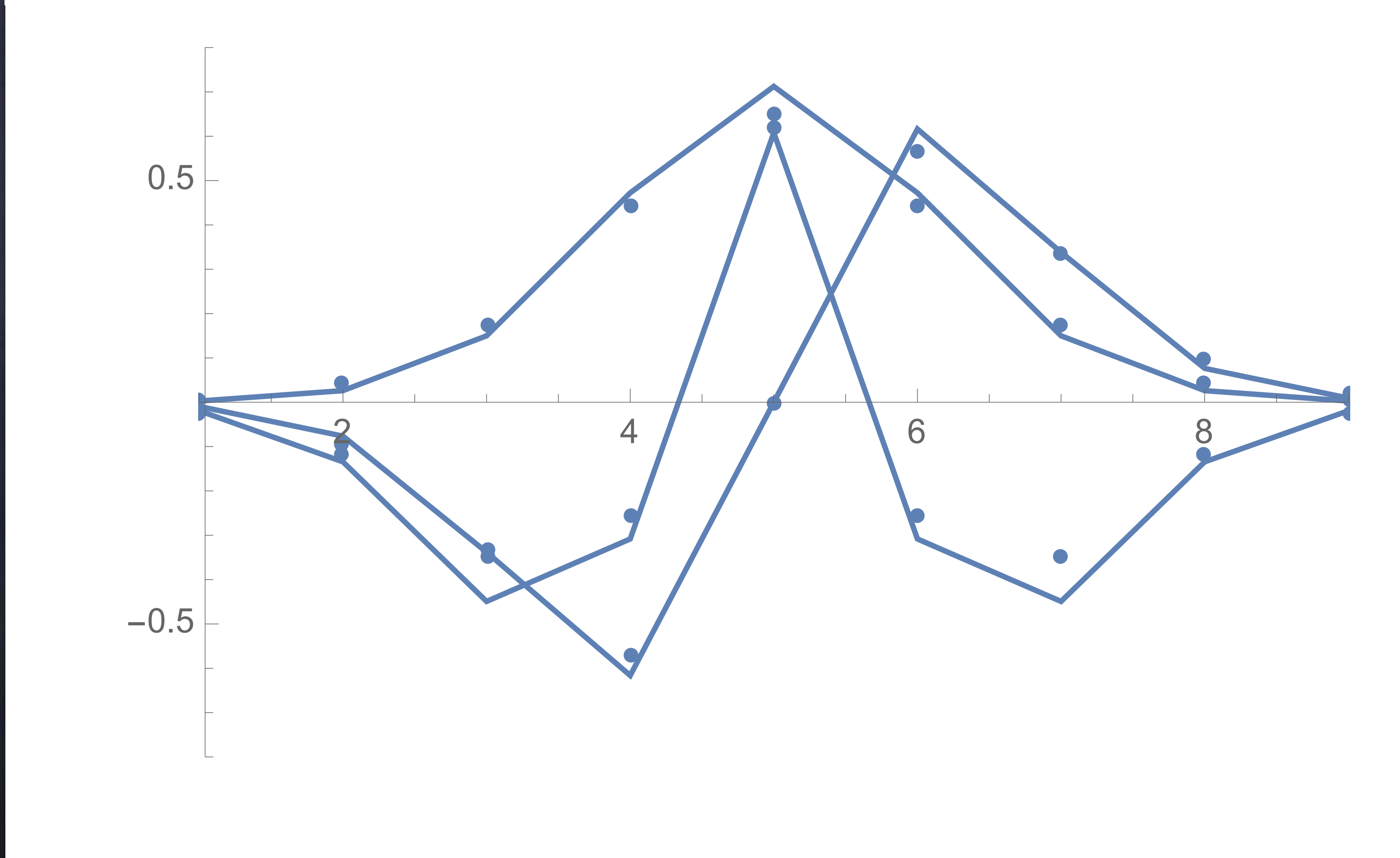
Terms that are new. Errors.

Stoquastic XX

$$H_{eff} = P(H) - \frac{\lambda^2 (L-3)}{2J}\mathrm{I} - \frac{3\lambda^2}{4J}\left[|1\rangle\langle 1| + |L\rangle\langle L|\right] - \frac{\lambda^2}{2J} P\left(\sum_{i=1}^{L-1} X_i X_{i+1}\right)$$

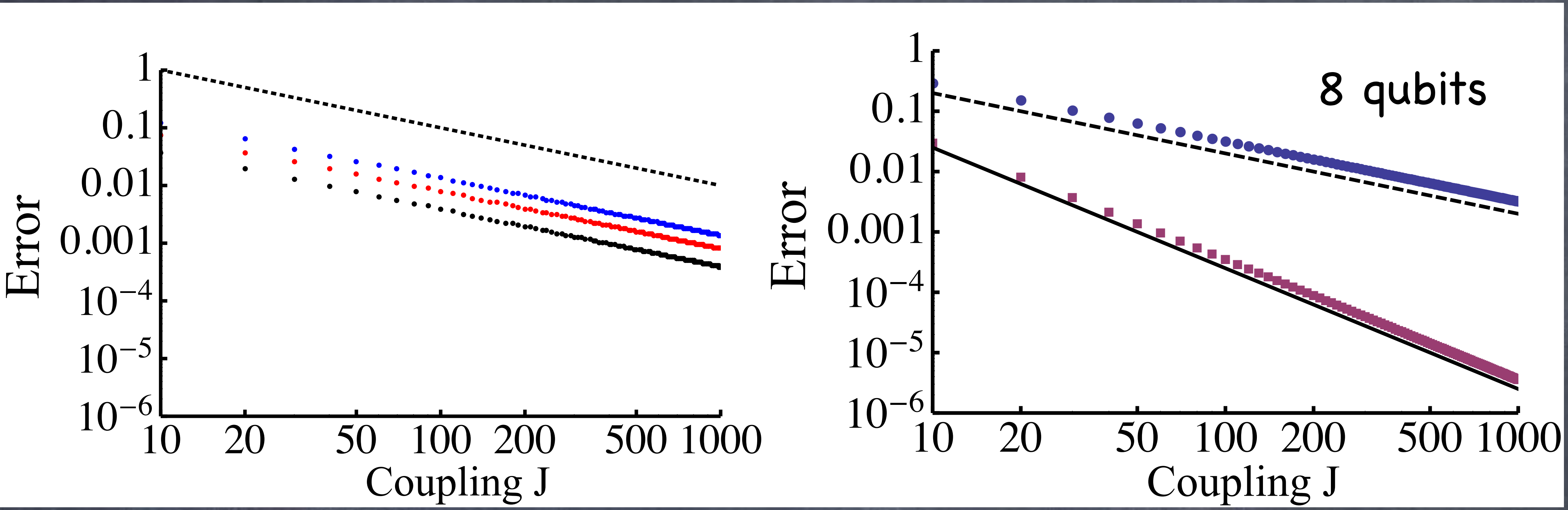


Linear Potential



SHO

Linear Potential



8, 10, 12 qubits should be sufficient to detect the scaling of the eigenvalues with penalty strength. Renormalizing coefficients should improve accuracy.

If you can engineer further terms (specifically XX) you should be able to see the scaling change.

Experiments observing these effects would fail to invalidate the presence of effects necessary for gadgets to work

Entanglement and delocalization

What is the entanglement of y<x with y>x?

Define reduced state: $\rho_x = Tr_{y>x}\rho$

And linear entropy (also Meyer-Wallach measure):

$$\rho_x = \frac{2^L}{2^L - 1}\left[1 - Tr\left(\rho_x^2\right)\right]$$

Entanglement and delocalization

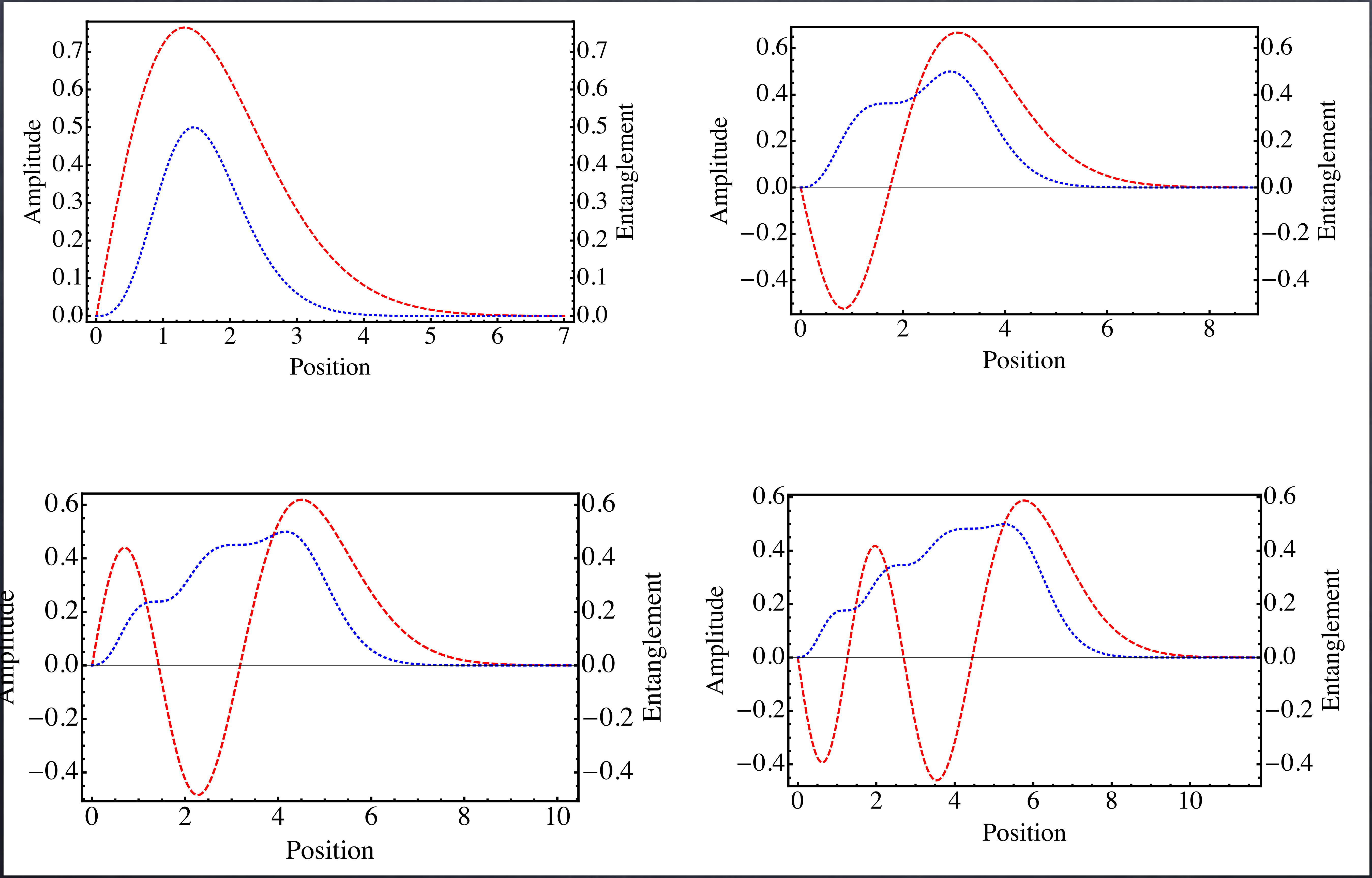
$$\rho_x = \frac{2^L}{2^L - 1}\left[1 - Tr\left(\rho_x^2\right)\right]$$

For kink states entanglement is really a measure of delocalization.

$$Tr\left(\rho_x^2\right) = \sum_{q=1}^{N} \left|\langle q|\psi\rangle\right|^4 + 2\sum_{q=1}^{x}\sum_{l=1}^{q-1}\left|\langle q|\psi\rangle\right|^2\left|\langle l|\psi\rangle\right|^2 + 2\sum_{q=x+1}^{x}\sum_{l=x+1}^{q-1}\left|\langle q|\psi\rangle\right|^2\left|\langle l|\psi\rangle\right|^2$$

Participation ratio

Entanglement and delocalization



Summary

- Non-scalable simulation is a good probe of properties relevant to post-quantum annealing AQC.
- Lets do some XX experiments!
- We will always ~~be at war with eurasia~~ need better locality reduction tecniques
- Case for quantumness in AQC will likely rely on many forms of indirect evidence.
- Worry: can techniques from fermion QMC be adapted to non-stoquastic XX?

Thanks!