Strong interacting photons in a synthetic magnetic field

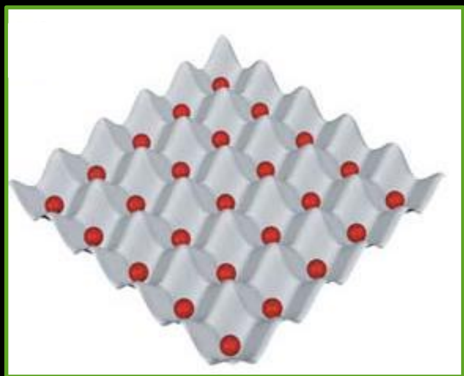
Pedram Roushan
Google Inc., Santa Barbara

Collaboration:

Eliot Kapit
Tulane university

Engineering platforms

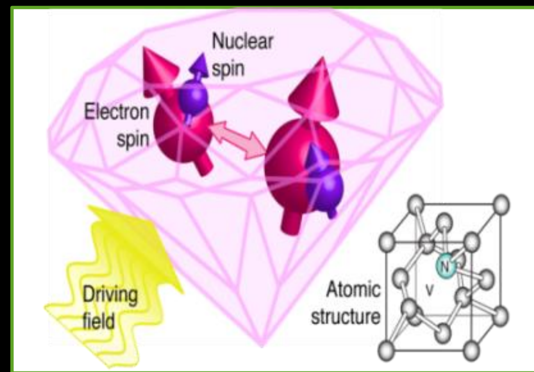
Ultra-cold atoms



Bloch, Nature Physics (2005)

Many body physics

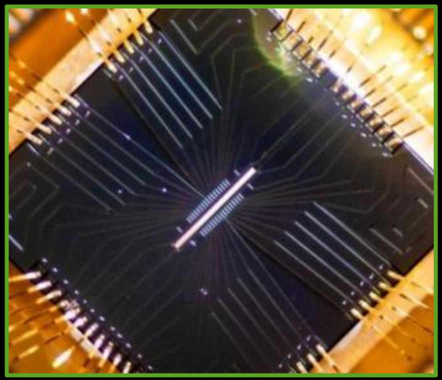
Spin qubits



Toyli, *et al.*, Nano Lett. 2010

Long coherence,
Room temp., Solid state

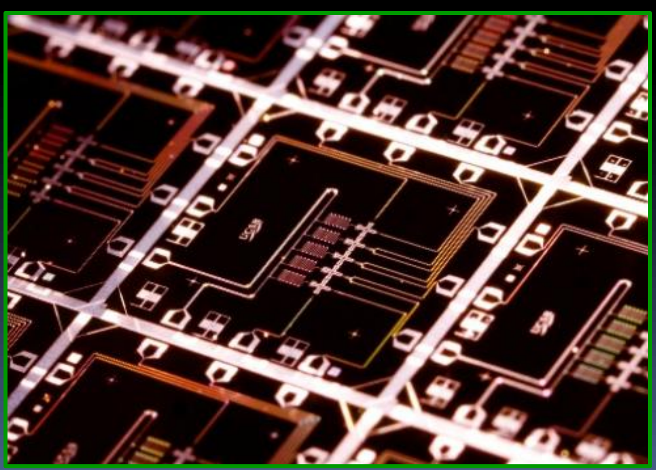
Trapped ions

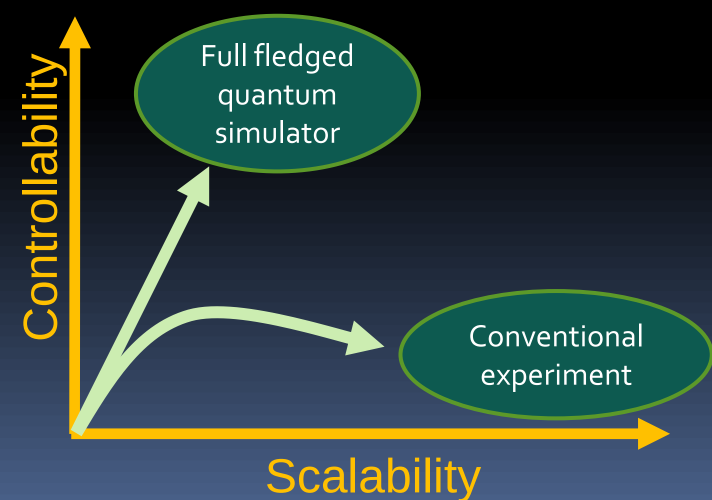


Monroe, *et al.*, Science 2013

High fidelity logic gates

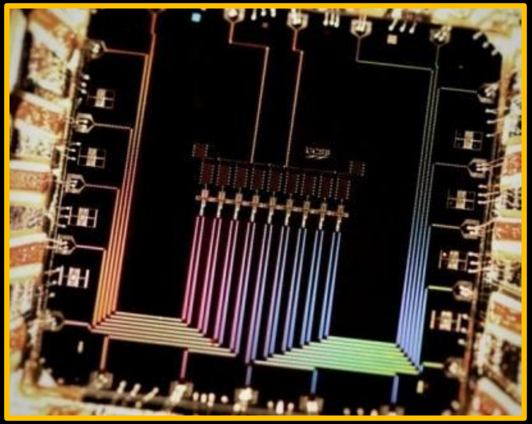
Superconducting circuits



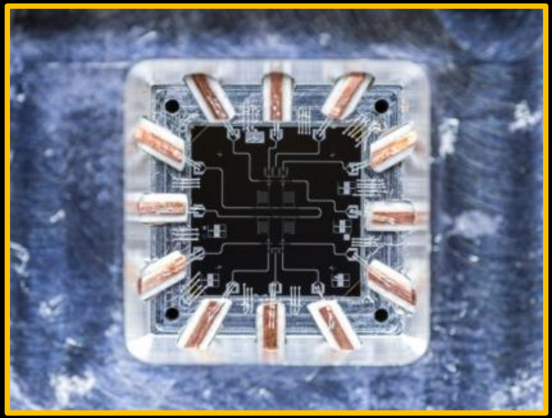


$+$

Superconducting qubits: xmon vs. gmon



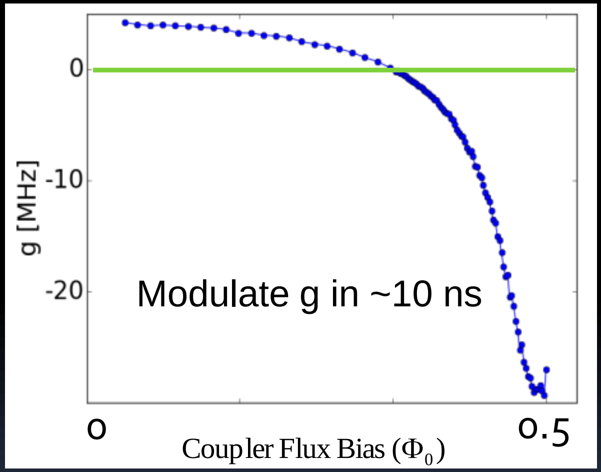
State-of-the-art in coherence



Mixing the best of two worlds?!

State-of-the-are in control

Xmon	gmon
simple	more wire
residue coupling	perfect off
fix coupling less control	adjustable coupling full control
frequency crowding	scalable
CZ gate and TLS	alternative CZ gates

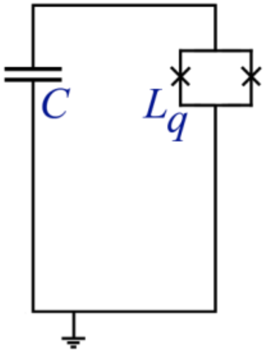


$$H = \sum_{Qubits} h_x(t)\,\sigma^X + h_y(t)\,\sigma^Y + h_z(t)\,\sigma^Z + \sum_{j\neq k} g_{jk}(t)\,(a_j^+ a_k + a_j a_k^+)$$

Tunable coupling

Barends *et al.*, Nature (2014)
Kelly *et al.* Nature (2015)

Chen *et al.*, PRL (2014)
Roushan, *et al.*, Nature (2014)



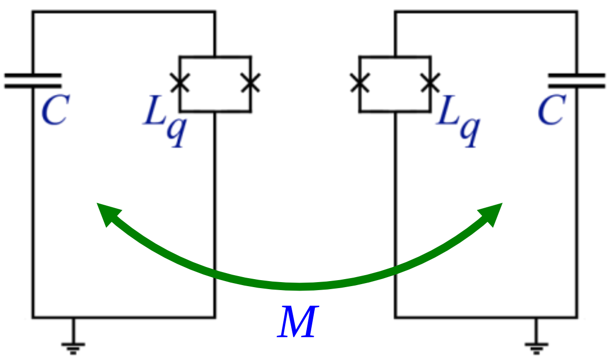
$$H_{Qubit} = \frac{\hat{Q}^2}{2C} - \frac{(\Phi_0/2\pi)^2}{L_q}\cos(\hat{\varphi})$$

$$\hat{\varphi} \to a^+ + a$$
$$\hat{Q} \to i(a^+ - a)$$
$$\hat{n} = a^+ a$$

$$H_{Qubit} = \underbrace{\frac{\hat{Q}^2}{2C} - \frac{(\Phi_0/2\pi)^2}{L_q}(1 - \frac{\hat{\varphi}^2}{2!}}_{H_{h.o.}} \underbrace{+ \frac{\hat{\varphi}^4}{4!} - \frac{\hat{\varphi}^6}{6!} + \ldots)}_{H_{int}}$$

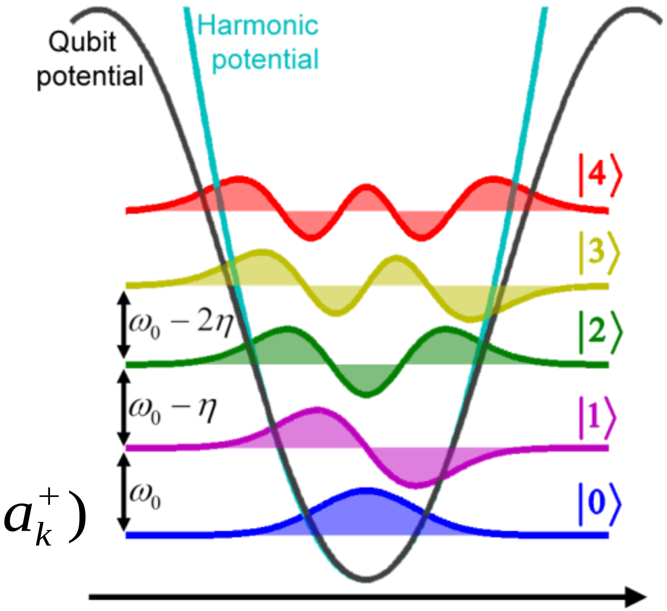
$$H_{h.o.} \xrightarrow[RWA]{} \hbar \frac{\Delta_0}{2}(\hat{n} + 1/2)$$

$$H_{int} \xrightarrow[RWA]{} -\frac{U_2}{2}\hat{n}(\hat{n}-1) + \frac{U_3}{6}\hat{n}(\hat{n}-1)(\hat{n}-2) + \ldots$$



$$H_{hop} = \frac{M}{2L_q^2}\hat{\varphi}_1\hat{\varphi}_2$$

$$H_{hop} \xrightarrow[RWA]{} g(a_j^+ a_k + a_j a_k^+)$$



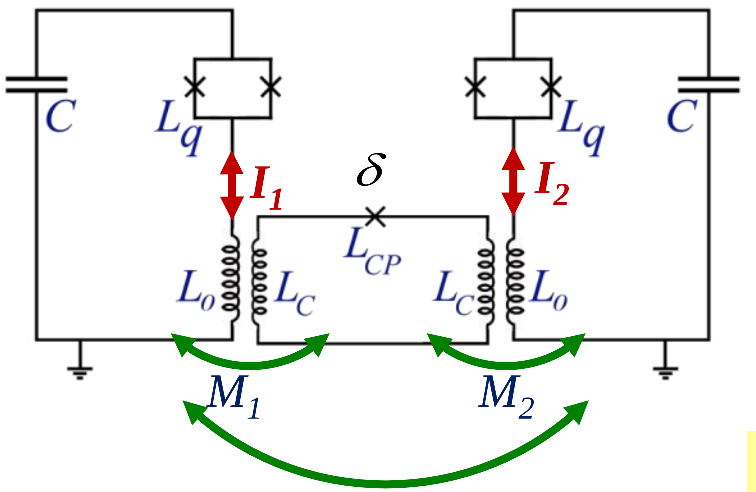
$$H = \sum_{Qubits} h_x(t)\,\sigma^X + h_y(t)\,\sigma^Y + h_z(t)\,\sigma^Z + \sum_{j\neq k} g_{jk}(t)(a_j^+ a_k + a_j a_k^+)$$

Tunable coupling

Barends *et al.*, Nature (2014)
Kelly *et al.* Nature (2015)

Chen *et al.*, PRL (2014)
Roushan, *et al.*, Nature (2014)

The gmon architecture



$$M = \frac{M_1 M_2}{L_{CP} + 2L_C}$$

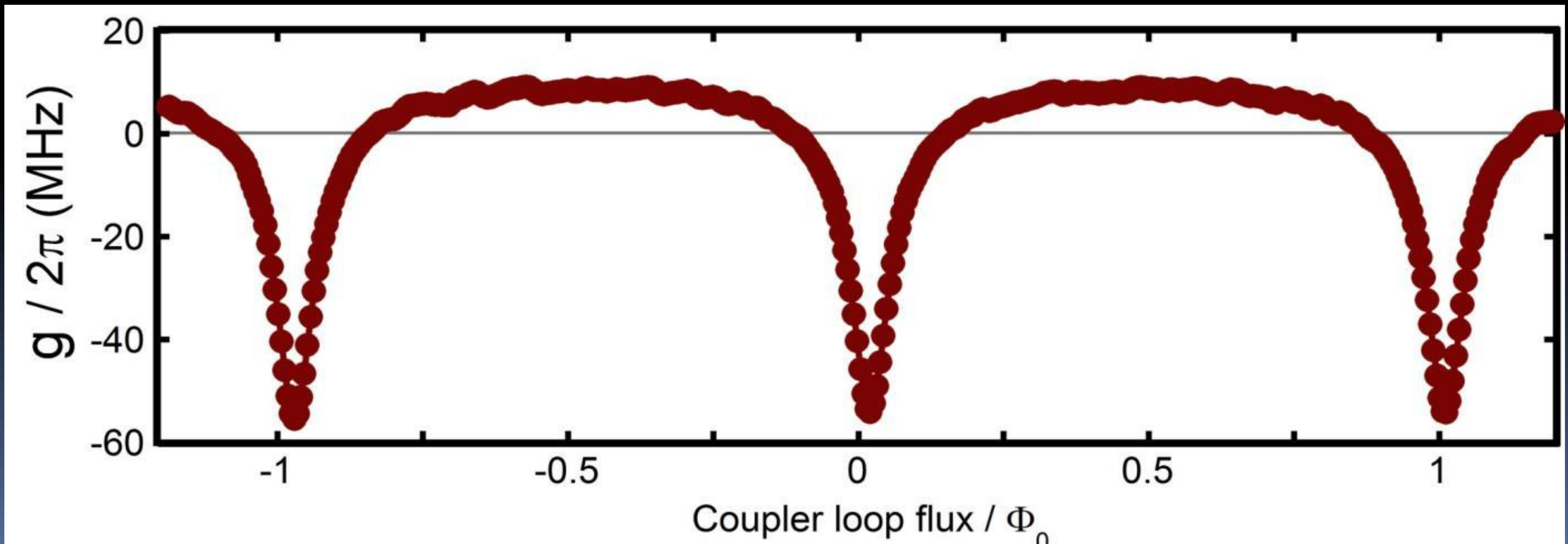
$$\omega_1 = \omega_0 (1 - \frac{M}{2L_q})$$

$$\omega_2 = \omega_0 (1 + \frac{M}{2L_q})$$

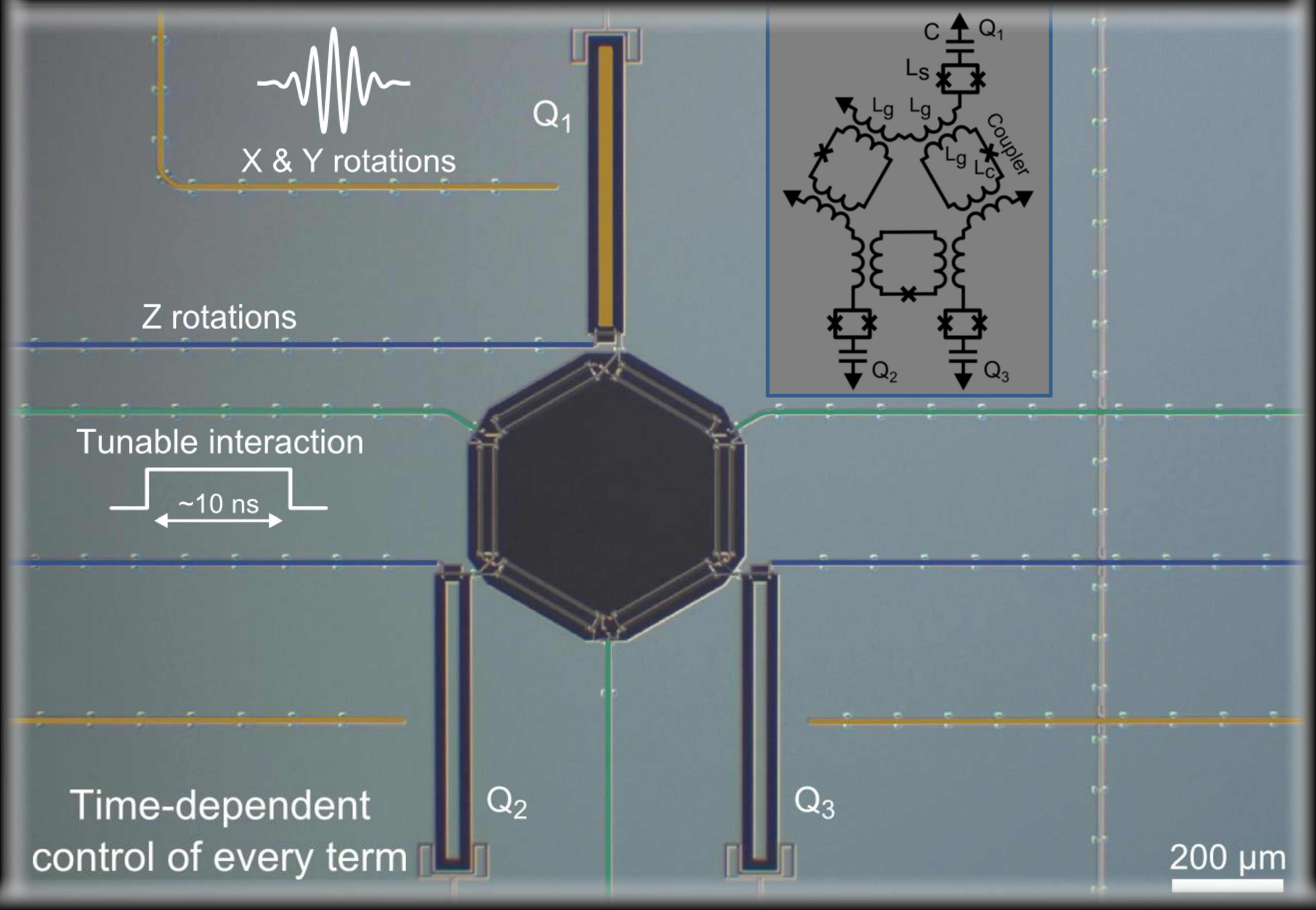
$$g \equiv \frac{\omega_2 - \omega_1}{2}$$

$$g / \omega_0 = \frac{M_1 M_2}{2L_q} \frac{\cos(\delta)}{2L_0 \cos(\delta) + L_C}$$


A homebuilt variometer

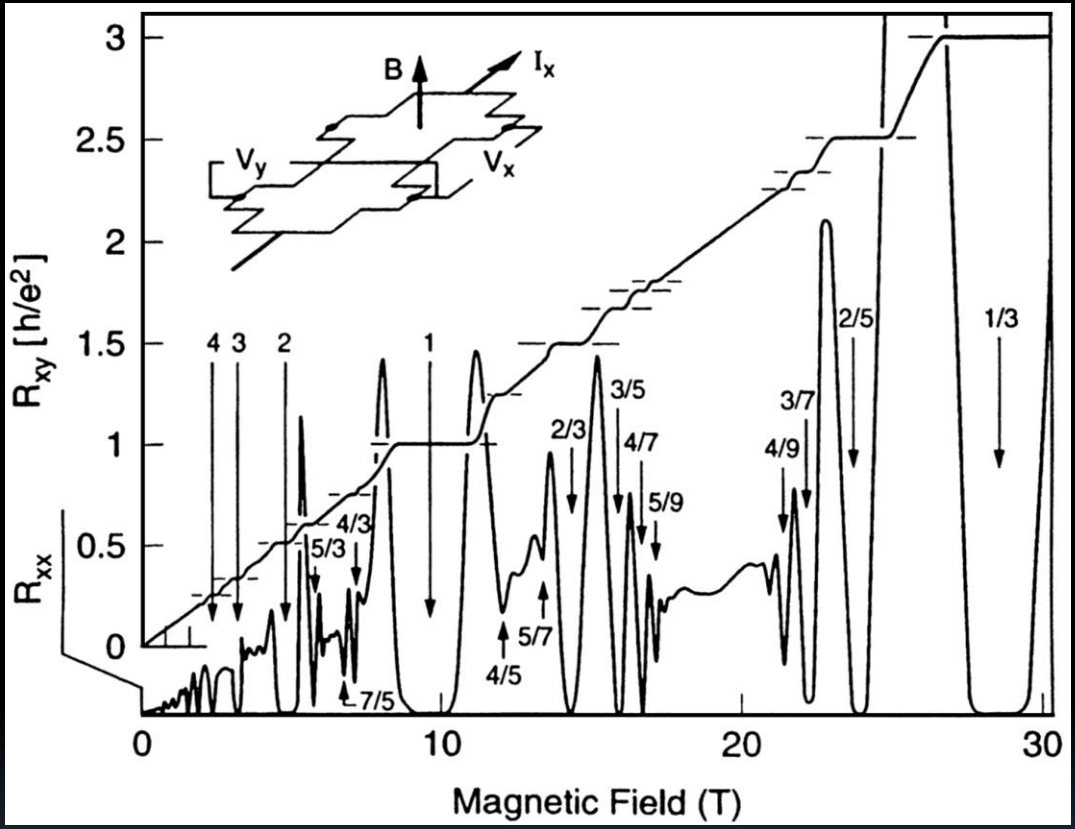


Fully controllable & coupled qubits

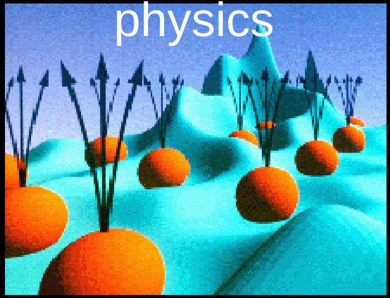


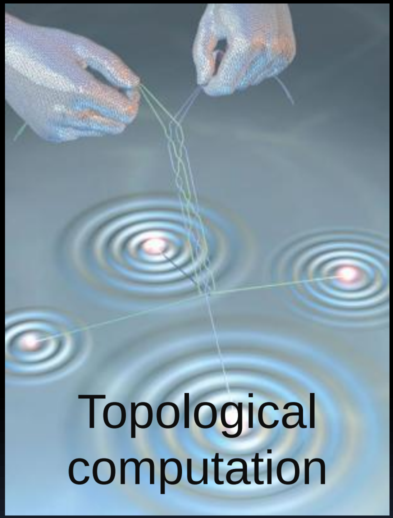
Many-body physics

1) Fermionic systems



Fundamental physics



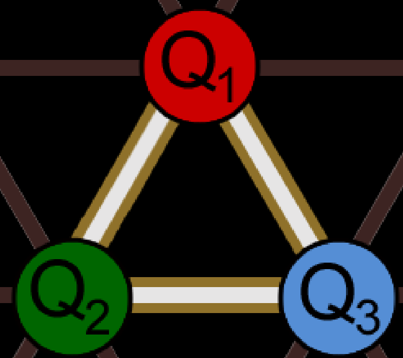


Topological computation

2) Bosonic systems

?

Many-body phases in interacting bosons



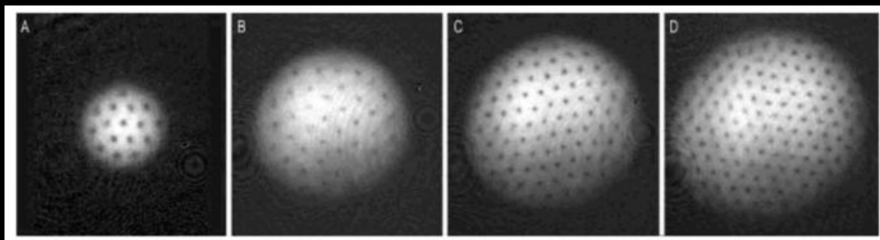
1) Strong interactions

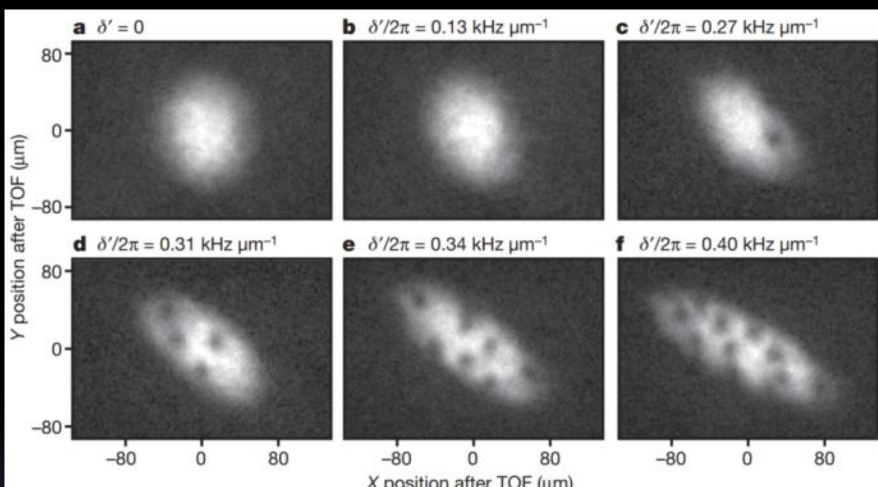
2) Synthetic gauge fields

3) Engineering flat band structure

Theory and experiments so far…

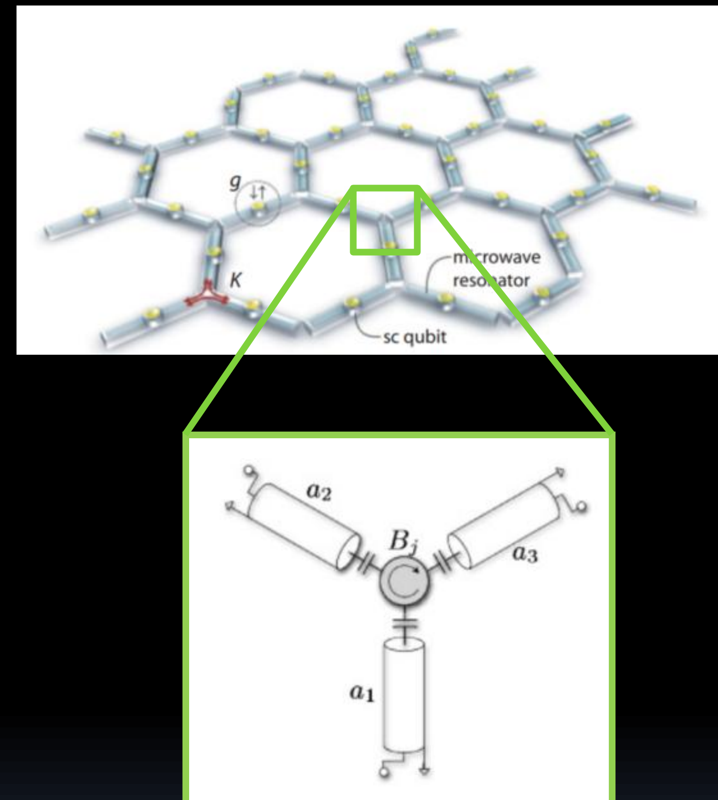
Cold atoms





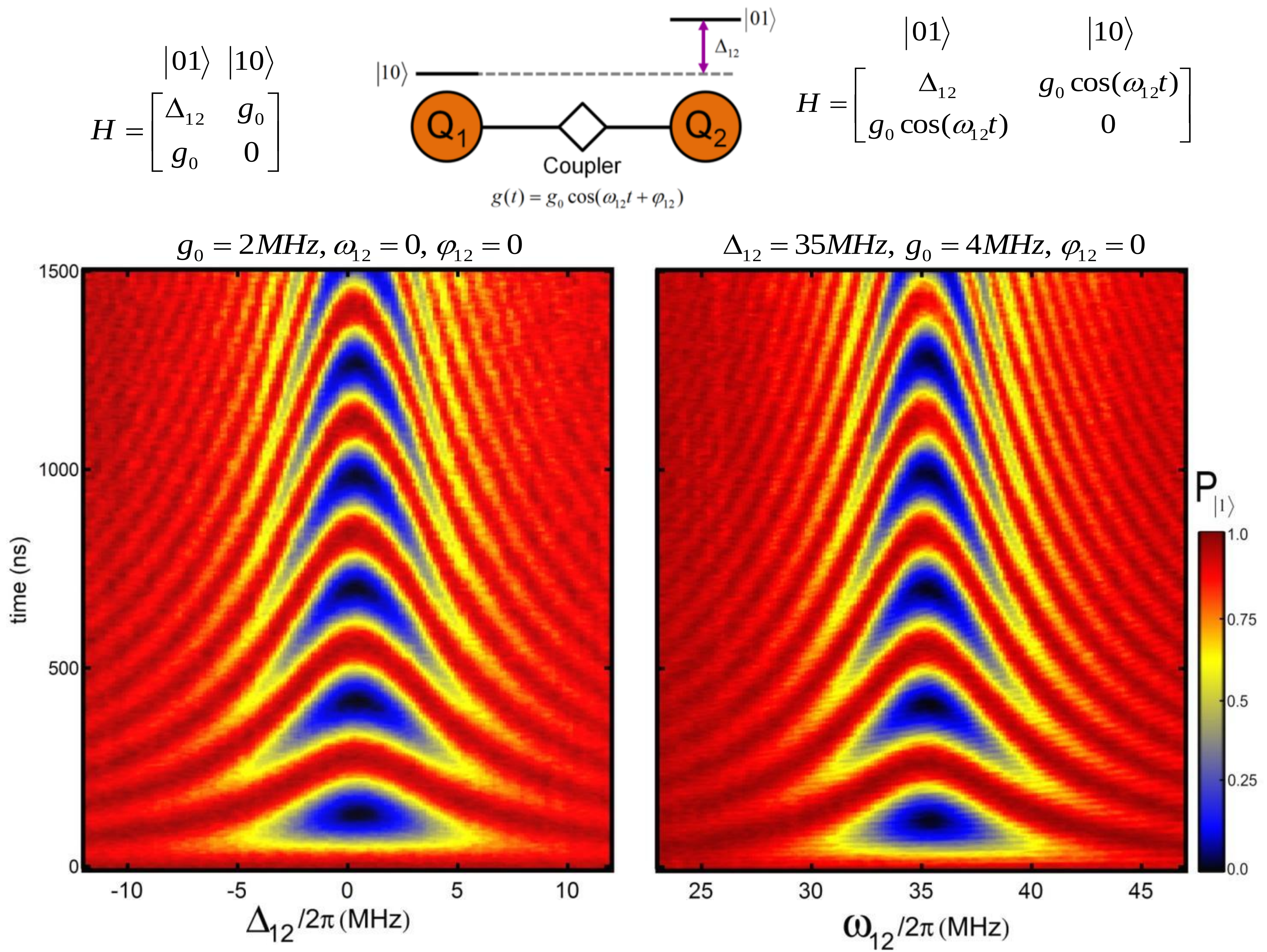
J. R. Abo-Shaeer et al., Science (2001)
B. Paredes *et al.*, Solid State communication (2003)
Y.-J. Lin *et al.*, Nature (2009)
M. Aidelsburger et al., PRL (2013)
V. Schweikhard et al., PRL (2014)
A. L. Fetter, RMP (2009)

Jaynes-Cummings lattice



J. Koch *et al.* , PRA (2010)
A. Nunnenkamp *et al.*, New J. of Physics (2011)
A. L. C. Hayward *et al.* , PRL (2012)
M. Hafezi *et al.*, PRB (2014)
J. Cho *et al.*, PRL (2008)

E. Kapit *et al.*, PRX (2014)



$H = \begin{array}{cc} |01\rangle & |10\rangle \end{array} \begin{bmatrix} \Delta_{12} & g_0 \\ g_0 & 0 \end{bmatrix}$
$|10\rangle$
$|01\rangle$
Δ_{12}
Q_1
Q_2
Coupler
$g(t) = g_0 \cos(\omega_{12} t + \varphi_{12})$
$H = \begin{array}{cc} |01\rangle & |10\rangle \end{array} \begin{bmatrix} \Delta_{12} & g_0 \cos(\omega_{12} t) \\ g_0 \cos(\omega_{12} t) & 0 \end{bmatrix}$
$g_0 = 2MHz, \omega_{12} = 0, \varphi_{12} = 0$
$\Delta_{12} = 35MHz, g_0 = 4MHz, \varphi_{12} = 0$
time (ns)
1500
1000
500
0
-10
-5
0
5
10
$\Delta_{12}/2\pi$ (MHz)
25
30
35
40
45
$\omega_{12}/2\pi$ (MHz)
$P_{|1\rangle}$
1.0
0.75
0.5
0.25
0.0

Engineering complex hopping

$$H(t) = -\sum_{j}^{3} \frac{\Delta_j}{2} \sigma_j^Z + \sum_{j \neq k}^{3} g_{jk}(t)(a_j^+ a_k + a_j a_k^+)$$

modulating coupling terms

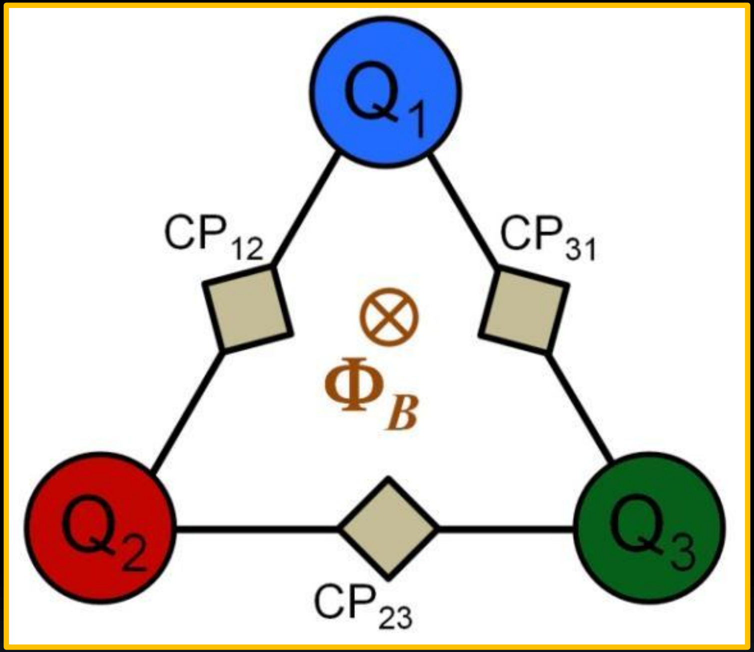
$$g_{jk}(t) = g_0 \cos(\omega_{jk} t + \varphi_{jk})$$

where,

$$\omega_{jk} = \Delta_j - \Delta_k$$

, and if

$$g_0 << \left|\Delta_j - \Delta_k\right|$$



$$\Phi_B \equiv \varphi_{12} + \varphi_{23} + \varphi_{31}$$

Using RWA, the effective Hamiltonian of the system is gauge-invariant

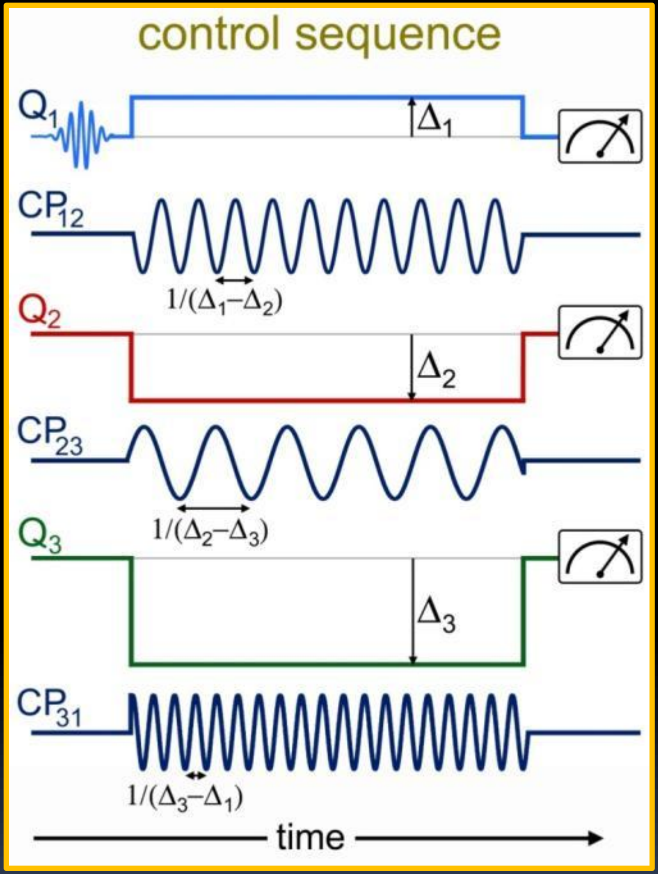
$$H_{eff} = \sum_{j \neq k}^{3} \frac{g_0}{2} (e^{i\varphi_{jk}} a_j^+ a_k + + e^{-i\varphi_{jk}} a_j a_k^+)$$

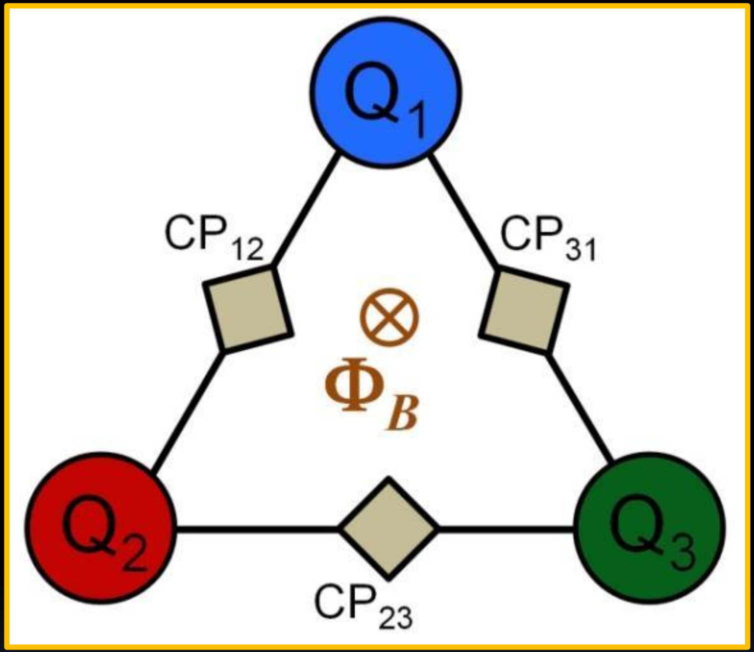
Universal two-qubit interactions: E. Kapit, PRA (2015)

Pulse sequence

In the lab:

$$H(t) = -\sum_{j}^{3} \frac{\Delta_j}{2} \sigma_j^Z + \sum_{j \neq k}^{3} g_{jk}(t)(a_j^+ a_k + a_j a_k^+)$$





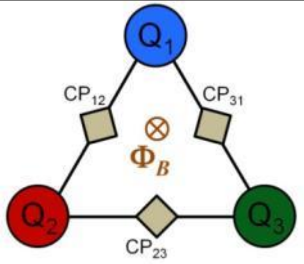
$$\Phi_B \equiv \varphi_{12} + \varphi_{23} + \varphi_{31}$$

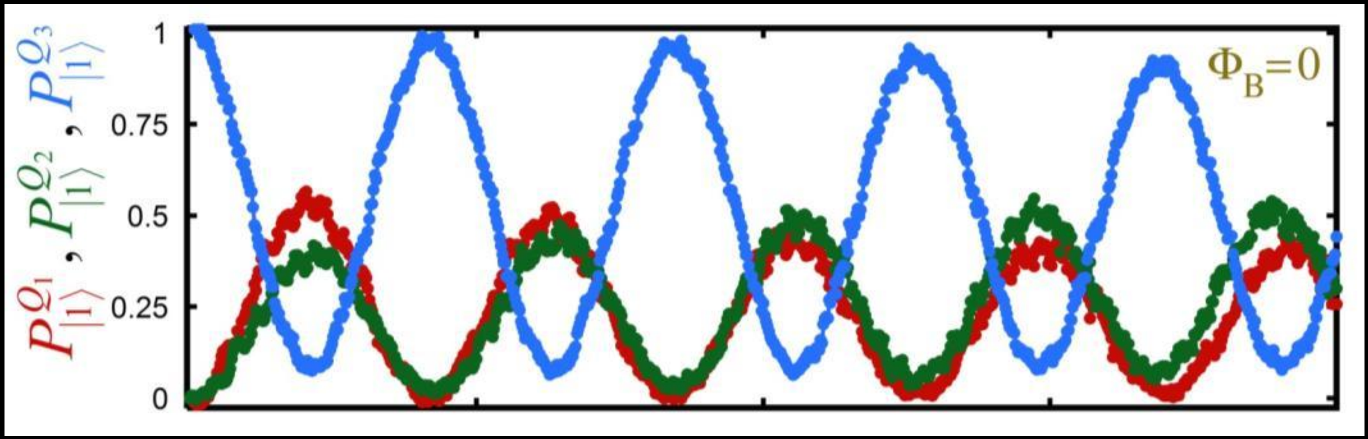
is gauge-invariant

In the rotating frame:

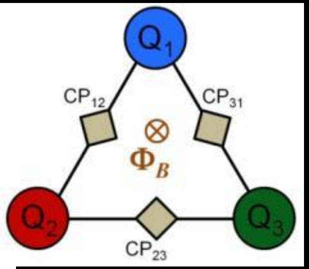
$$H_{eff} = \sum_{j \neq k}^{3} \frac{g_0}{2} (e^{i\varphi_{jk}} a_j^+ a_k + + e^{-i\varphi_{jk}} a_j a_k^+)$$

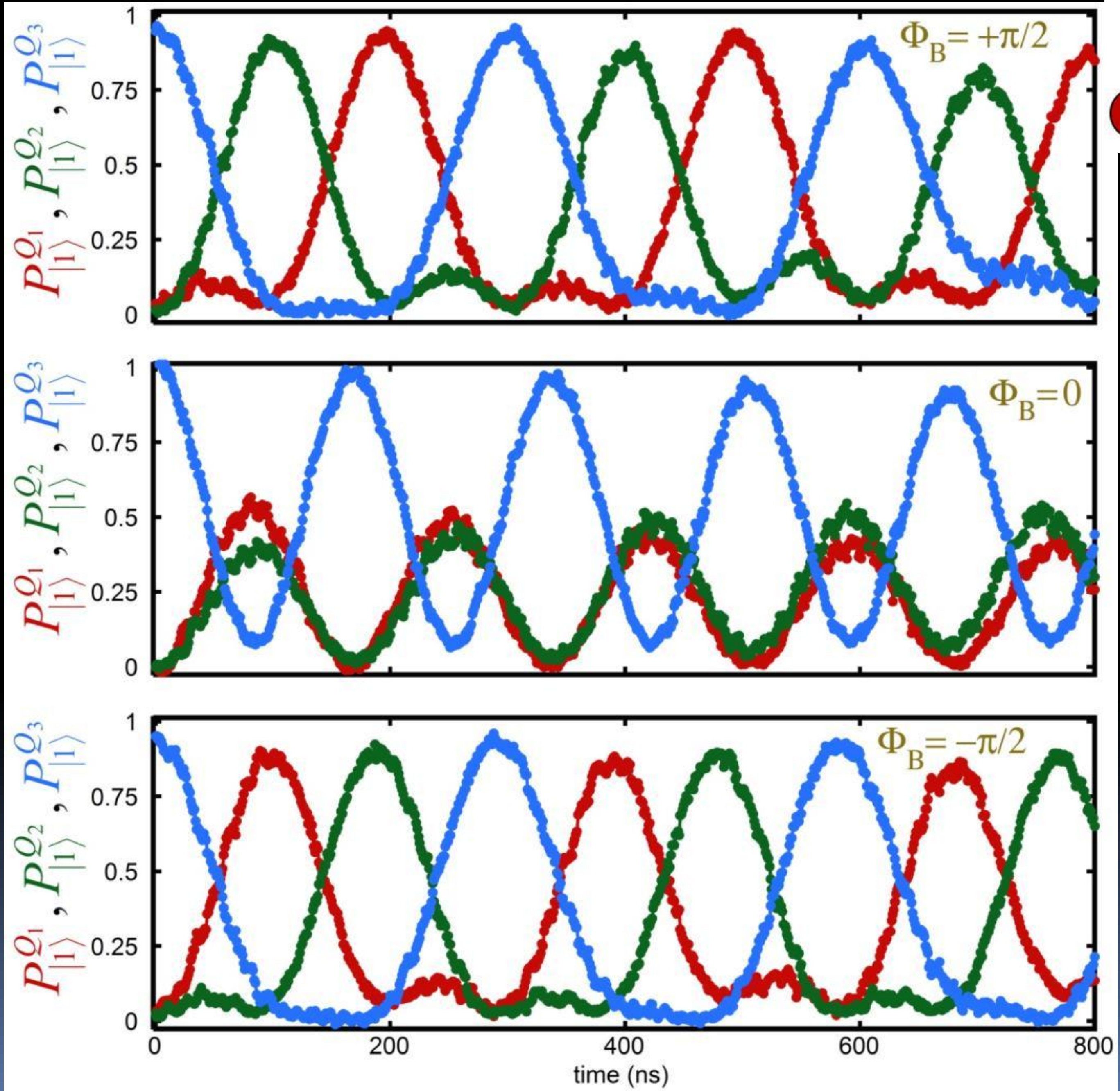
Single photon circulation



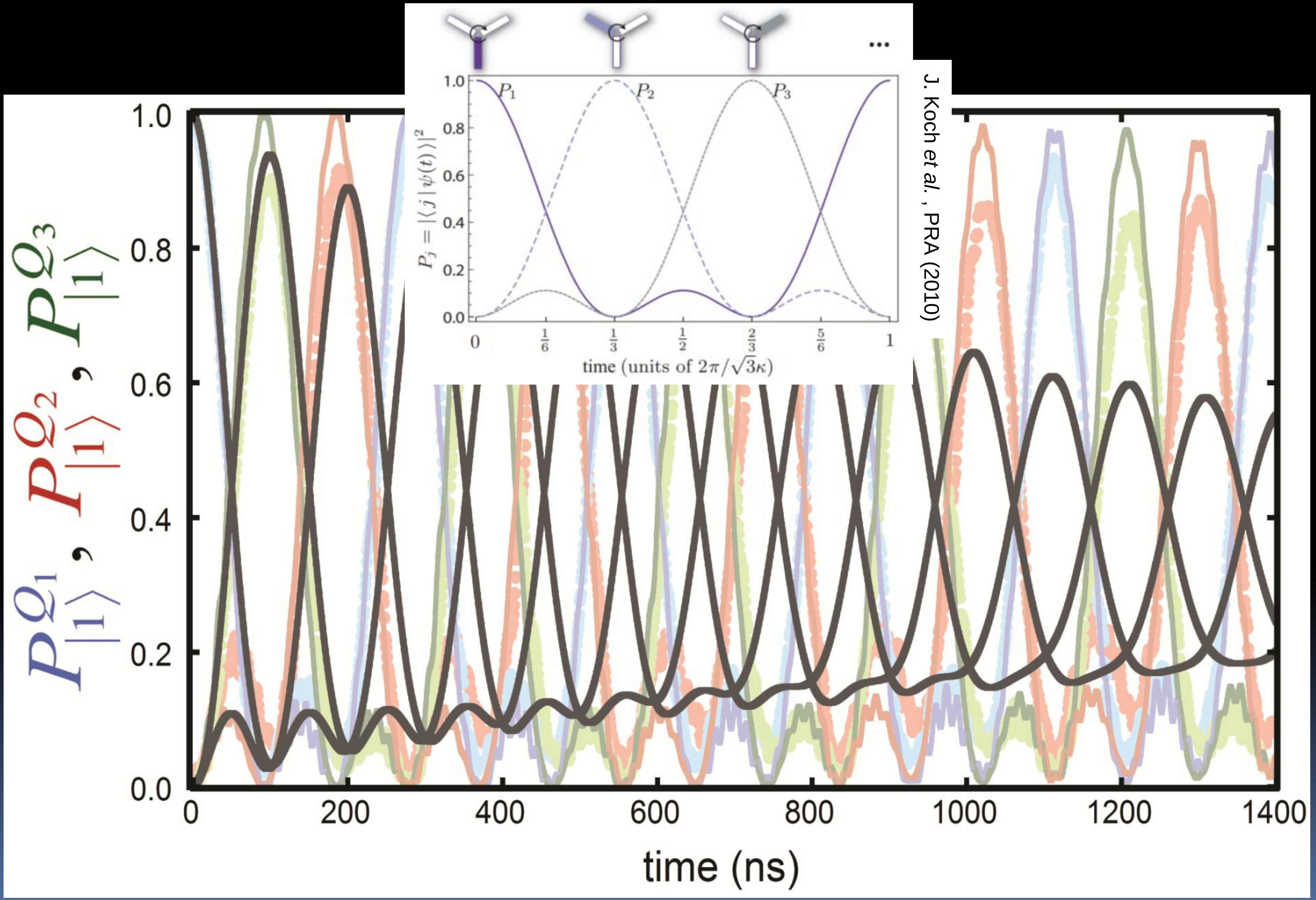


Single photon circulation



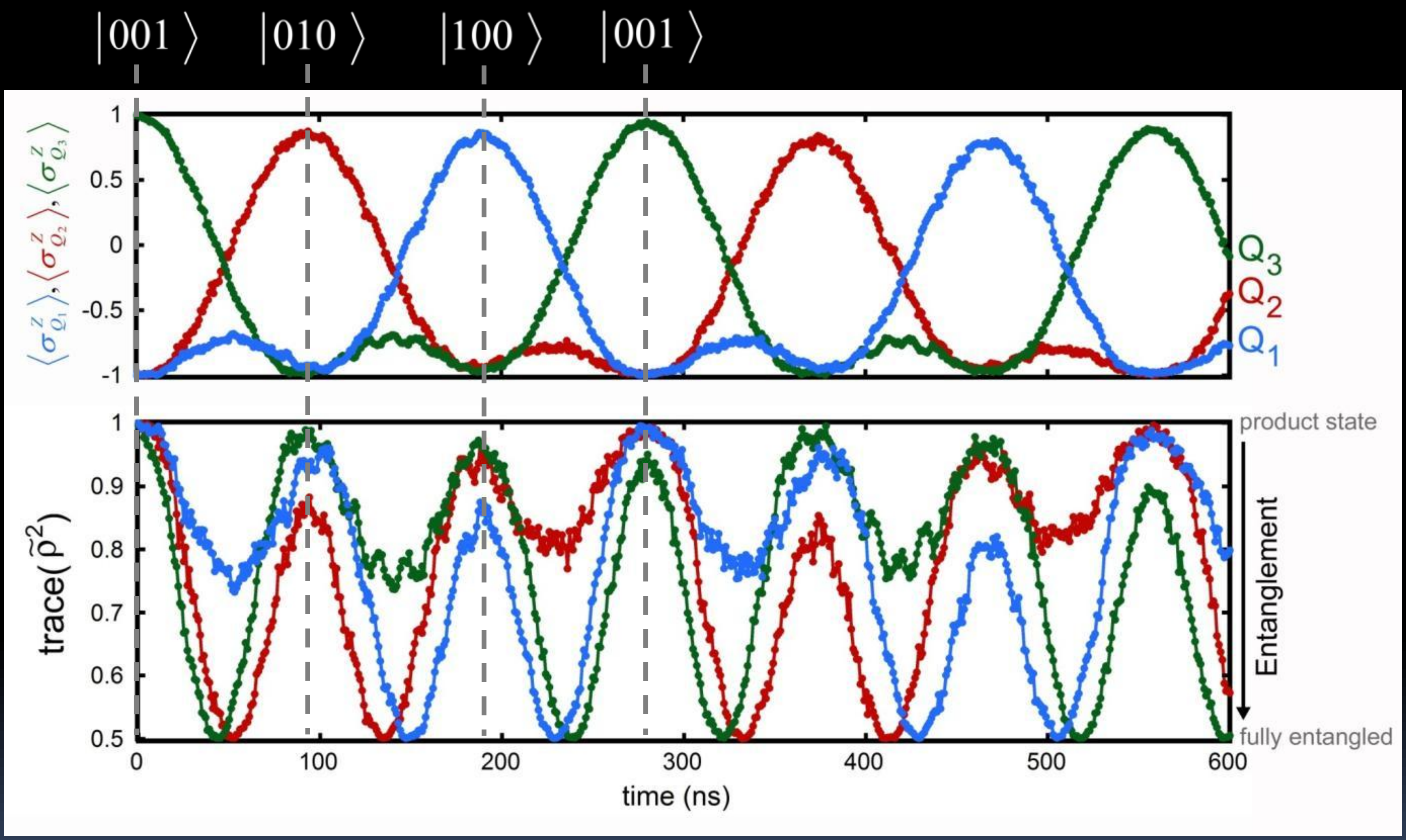


Behaves better than advertised !



J. Koch *et al.* , PRA (2010)

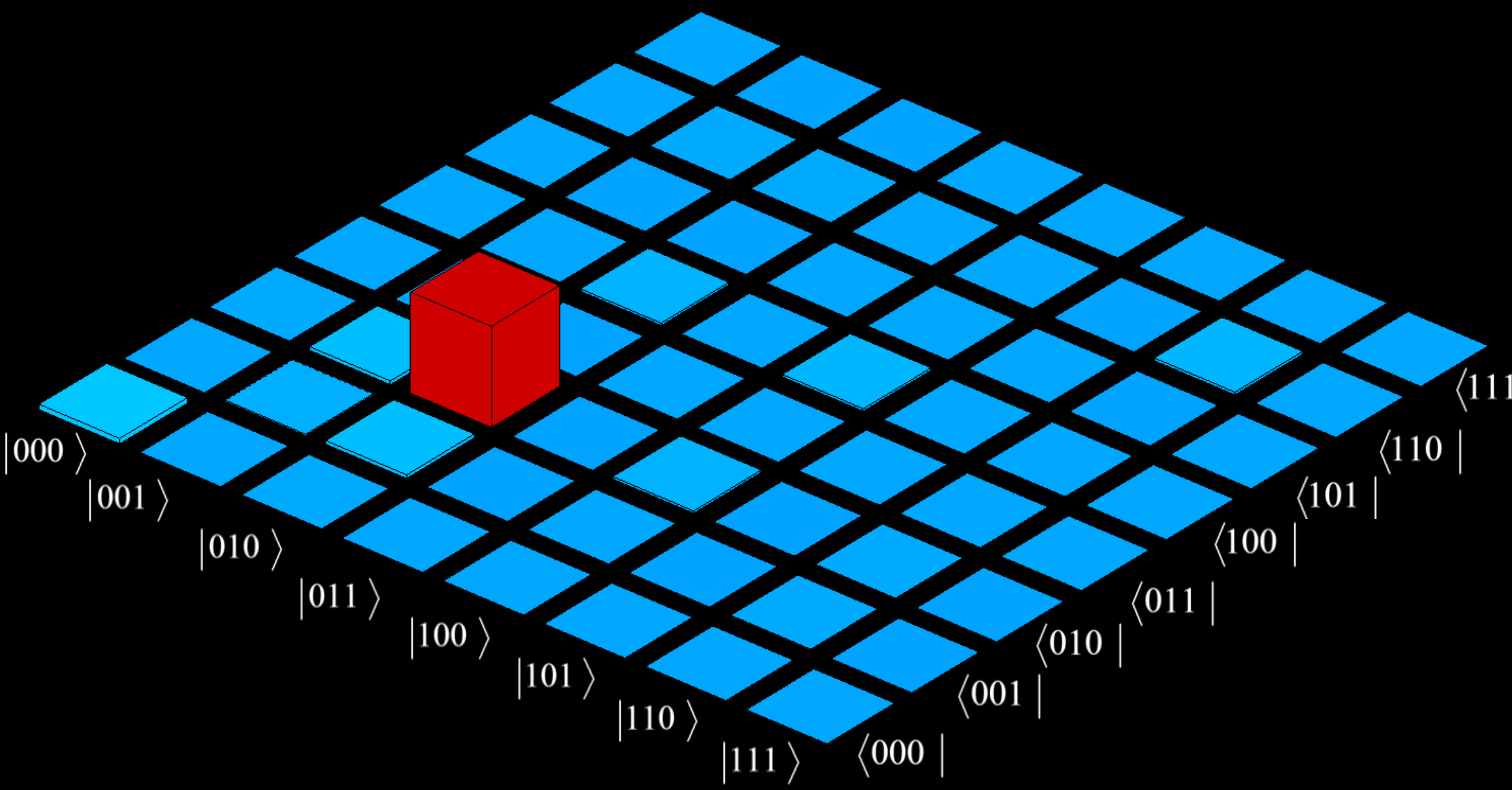
Entanglement circulation



$$\tilde{\rho} = \begin{bmatrix} 1/2 + <\sigma^Z> & <\sigma^X> - i<\sigma^Y> \\ <\sigma^X> + i<\sigma^Y> & 1/2 + <\sigma^Z> \end{bmatrix}$$

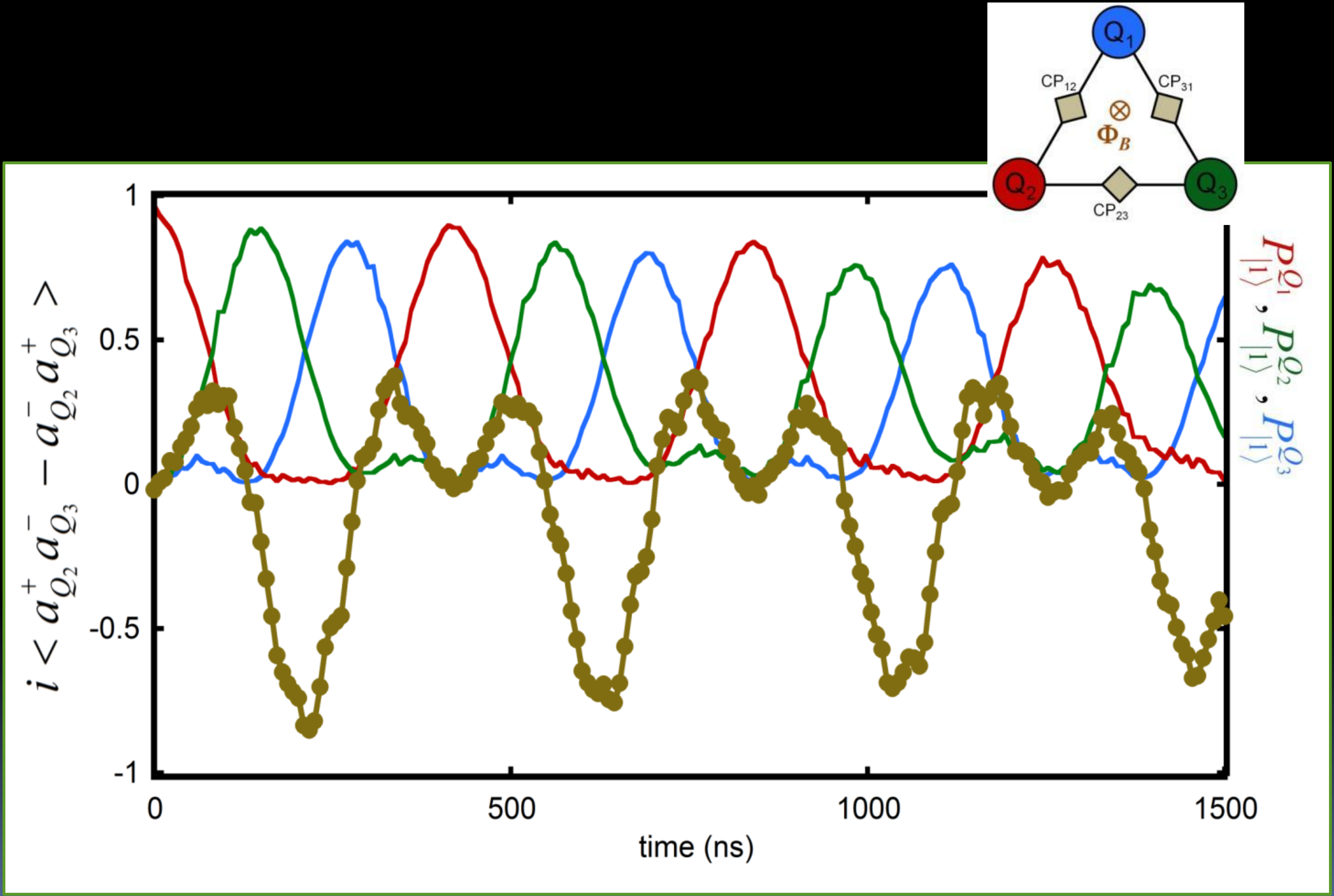
OR

$$tr(\tilde{\rho}^2) = \frac{1 + |V_{Bloch}|^2}{2}$$



|000⟩
|001⟩
|010⟩
|011⟩
|100⟩
|101⟩
|110⟩
|111⟩
⟨000|
⟨001|
⟨010|
⟨011|
⟨100|
⟨101|
⟨110|
⟨111

Measuring quantum correlations



Signature of strong interacting photons

$$H_{int} = -\frac{U_2}{2}\hat{n}(\hat{n}-1) + \frac{U_3}{6}\hat{n}(\hat{n}-1)(\hat{n}-2) + \ldots \qquad U_2 = U_3 = 220MHz$$

$$H_{eff} = \sum_{j\neq k}^{3} \frac{g_0}{2}\left(e^{i\varphi_{jk}} a_j^{+} a_k + +e^{-i\varphi_{jk}} a_j a_k^{+}\right) \qquad g_0 = 5MHz$$

$\psi_0 = |011\rangle$

Two photon (darkon)

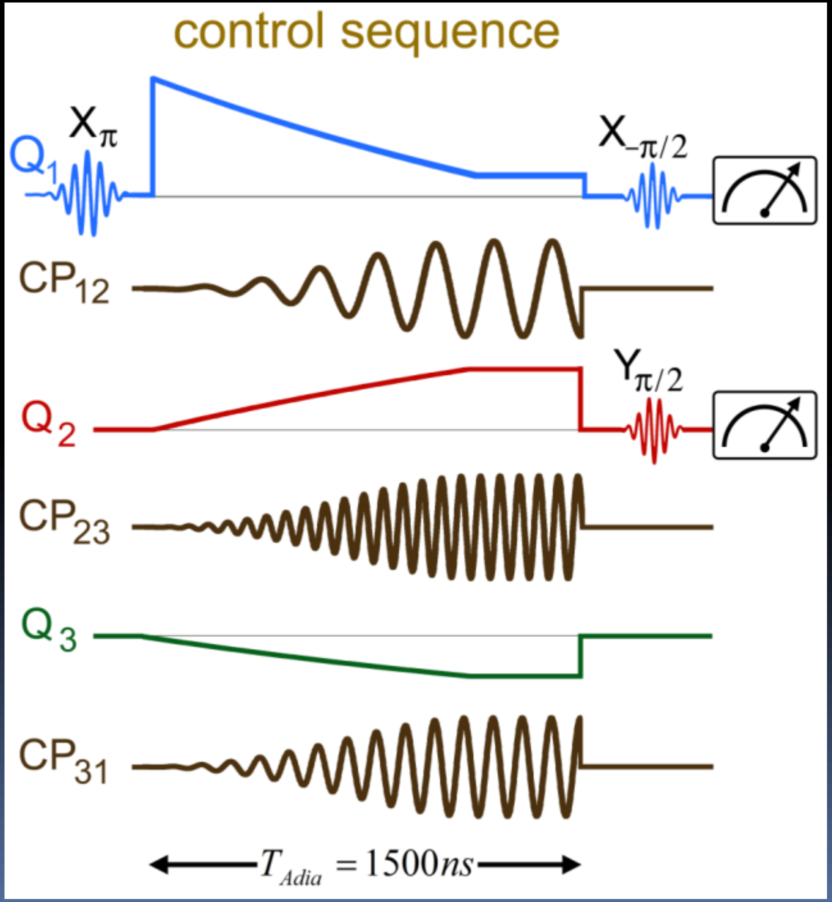
$P^{Q_1}_{|1\rangle}$, $P^{Q_2}_{|1\rangle}$, $P^{Q_3}_{|1\rangle}$

Ground state chirality

$$H(t=0) = \begin{bmatrix} \Delta_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad H_{eff}(t=T_{Adia}) = \begin{bmatrix} 0 & g_0 & g_0 e^{i\Phi_B} \\ g_0 & 0 & g_0 \\ g_0 e^{-i\Phi_B} & g_0 & 0 \end{bmatrix}$$

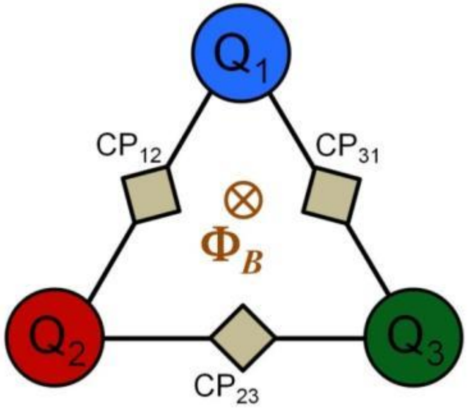
Adiabatic ramping

$$\psi_0 = |100\rangle \longrightarrow \psi_{T_{Adia}} = ?$$



$$\hat{I}_{Q_1}^{in} - \hat{I}_{Q_1}^{out} = \frac{\partial \hat{n}_{Q_1}}{\partial t}$$

$$\frac{\partial \hat{n}_{Q_1}}{\partial t} = \frac{i}{\hbar}[\hat{H}, \hat{n}_{Q_1}]$$



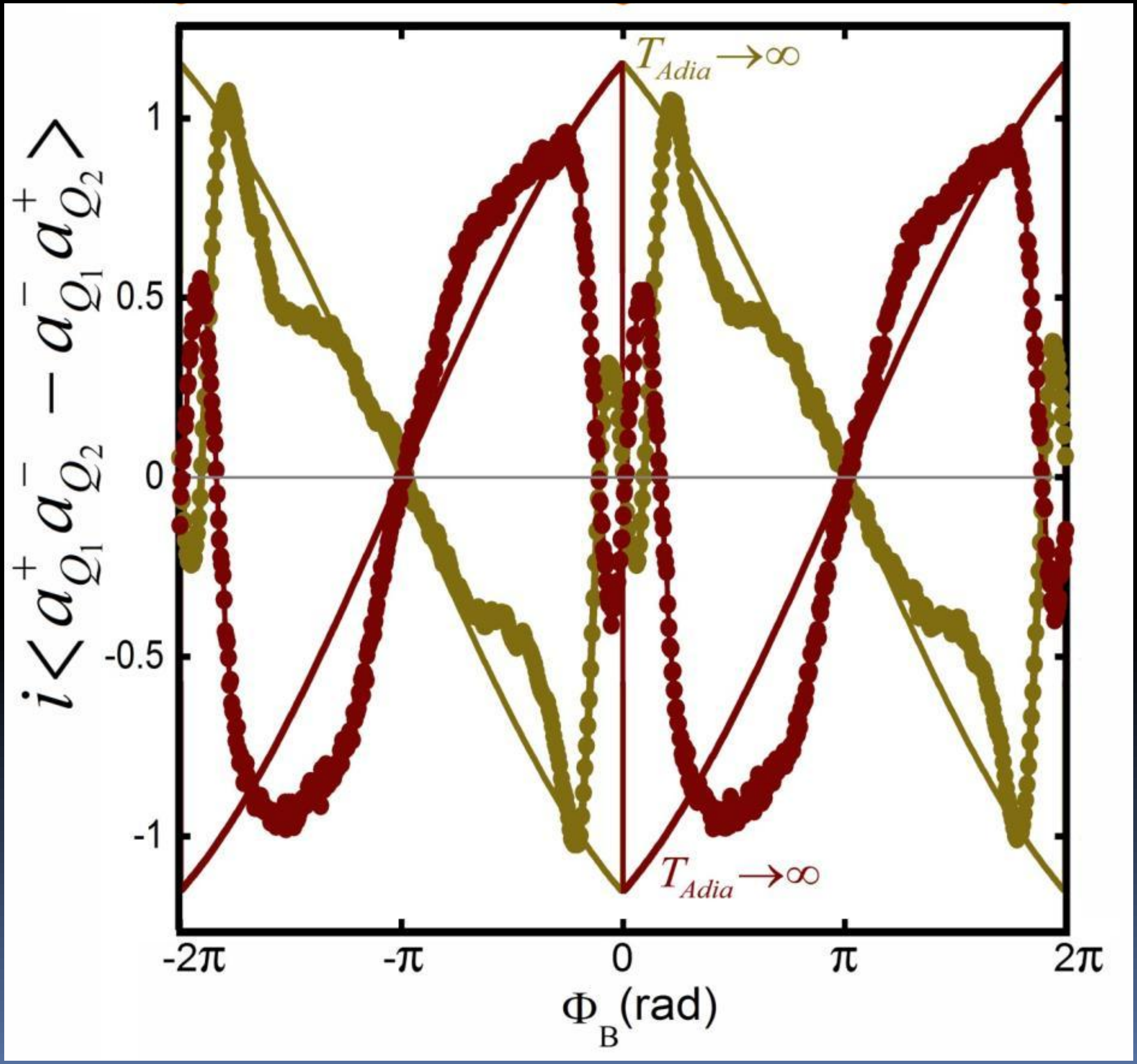
define:

$$\hat{I}_{Q_1\to Q_2} \equiv i(e^{i\varphi_{12}} a_{Q_1}^{+} a_{Q_2}^{-} - e^{-i\varphi_{12}} a_{Q_1}^{-} a_{Q_2}^{+})$$

measure:

$$\hat{I}_{Q_1\to Q_2} = \sigma_{Q1}^{X}\sigma_{Q2}^{Y} - \sigma_{Q1}^{Y}\sigma_{Q2}^{X}$$

Ground state chirality



Holistic picture

$$
\begin{array}{cccc}
 & |001\rangle & |010\rangle & |100\rangle \\
H_{eff}(\Phi_B)= & \left[\begin{array}{c} 0 \\ g_0 \\ g_0 e^{-i\Phi_B} \end{array}\right. & \begin{array}{c} g_0 \\ 0 \\ g_0 \end{array} & \left.\begin{array}{c} g_0 e^{i\Phi_B} \\ g_0 \\ 0 \end{array}\right]
\end{array}
$$

Lemma 1:

$$\psi_{\Phi_B=0} = \frac{|001\rangle + |010\rangle + |100\rangle}{\sqrt{3}}$$

is an eigenstate of H_{eff} at $\Phi_B=0$,

eigenstates on that manifold have this form

$$\psi_{\Phi_B} = \frac{e^{2i\Phi_B/3}|001\rangle + e^{i\Phi_B/3}|010\rangle + |100\rangle}{\sqrt{3}}$$

Lemma 2:

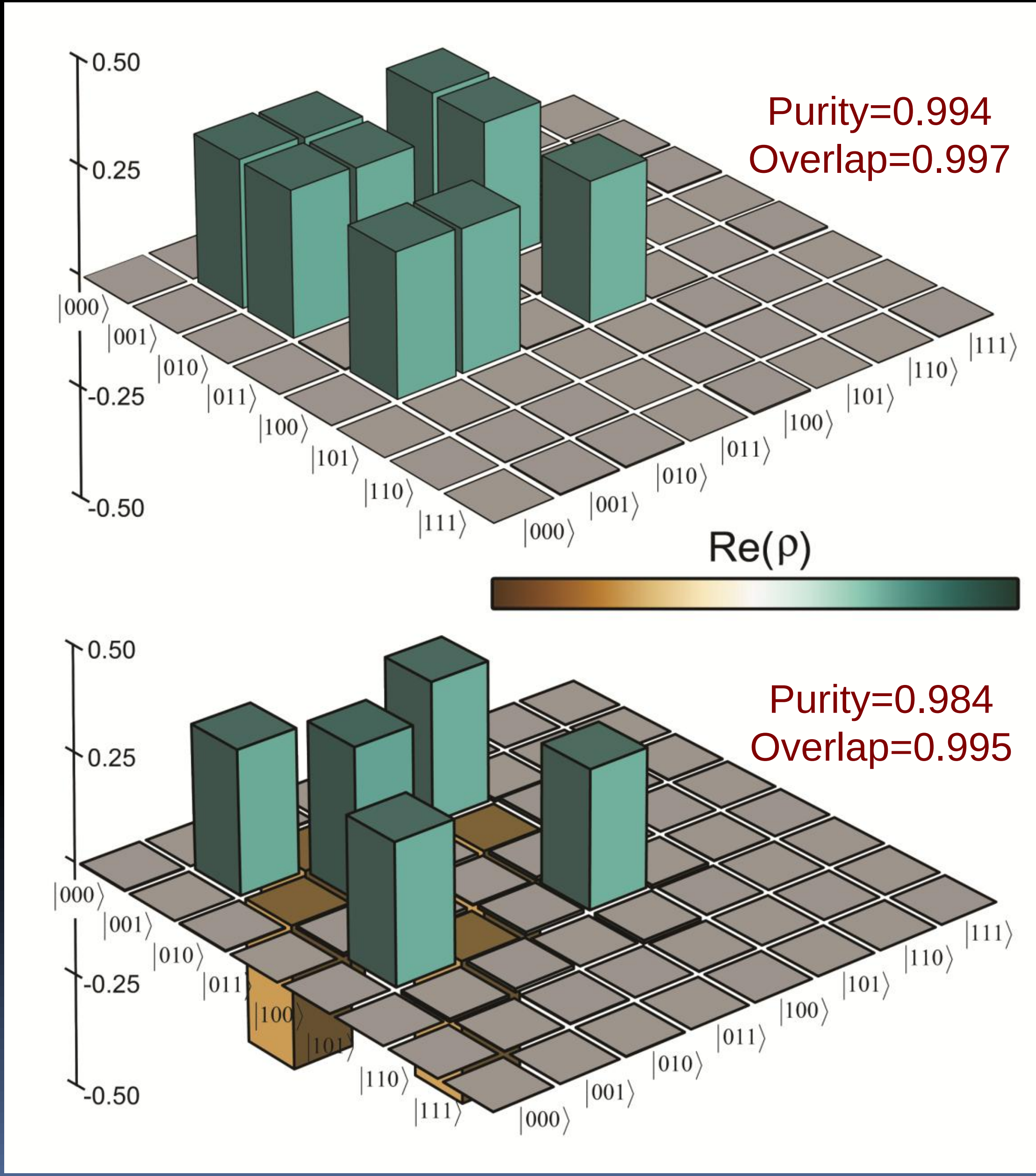
$$\psi_{\Phi_B=\pi} = \frac{|001\rangle - |010\rangle + |100\rangle}{\sqrt{3}}$$

is an eigenstate of H_{eff} at $\Phi_B=\pi$,

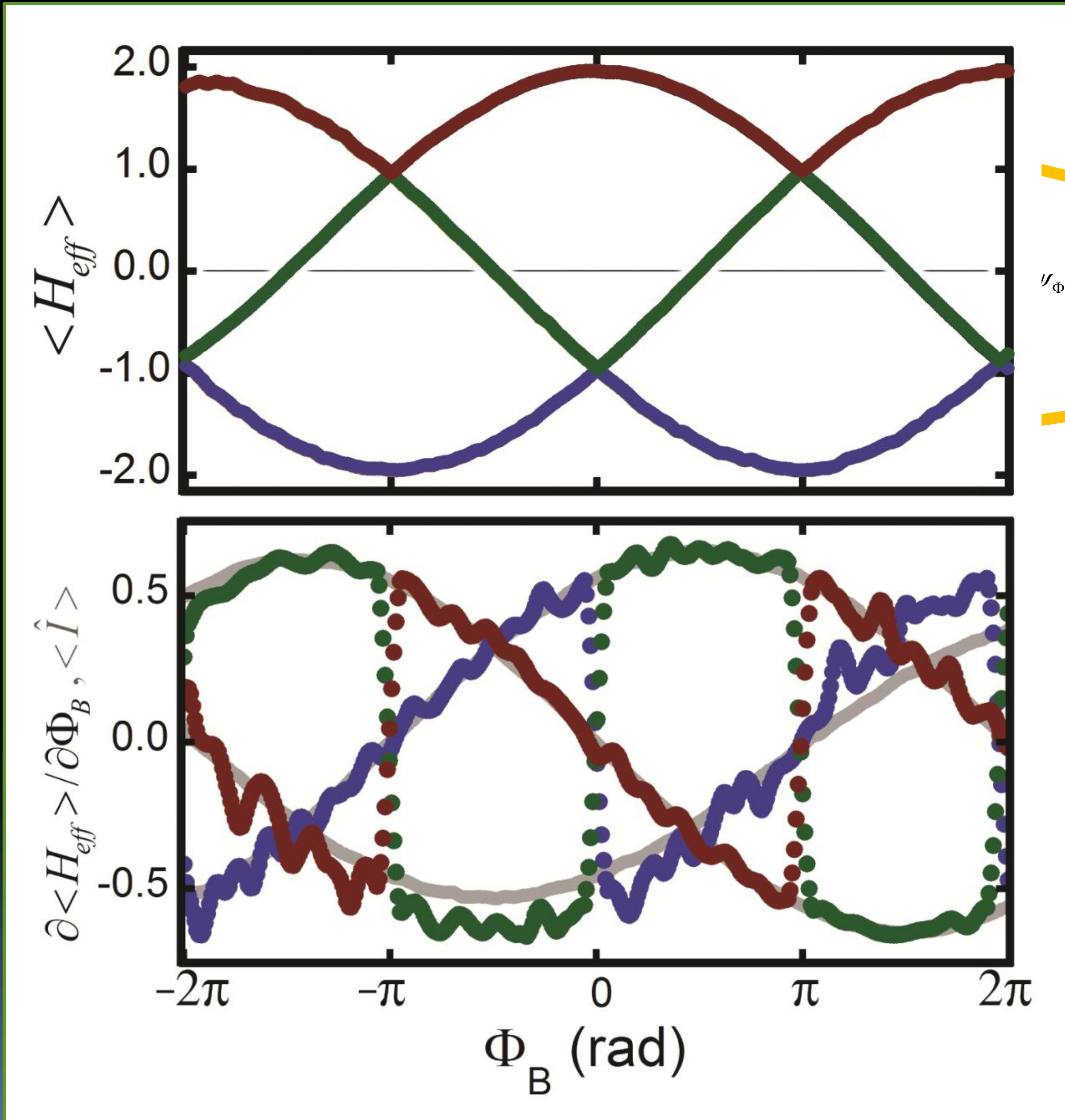
eigenstates on that manifold have this form

$$\psi_{\Phi_B} = \frac{e^{2i\phi_B/3}|001\rangle - e^{i\phi_B/3}|010\rangle + |100\rangle}{\sqrt{3}}$$

$$\phi_B = \Phi_B + \pi$$



Current phase relation



W-state

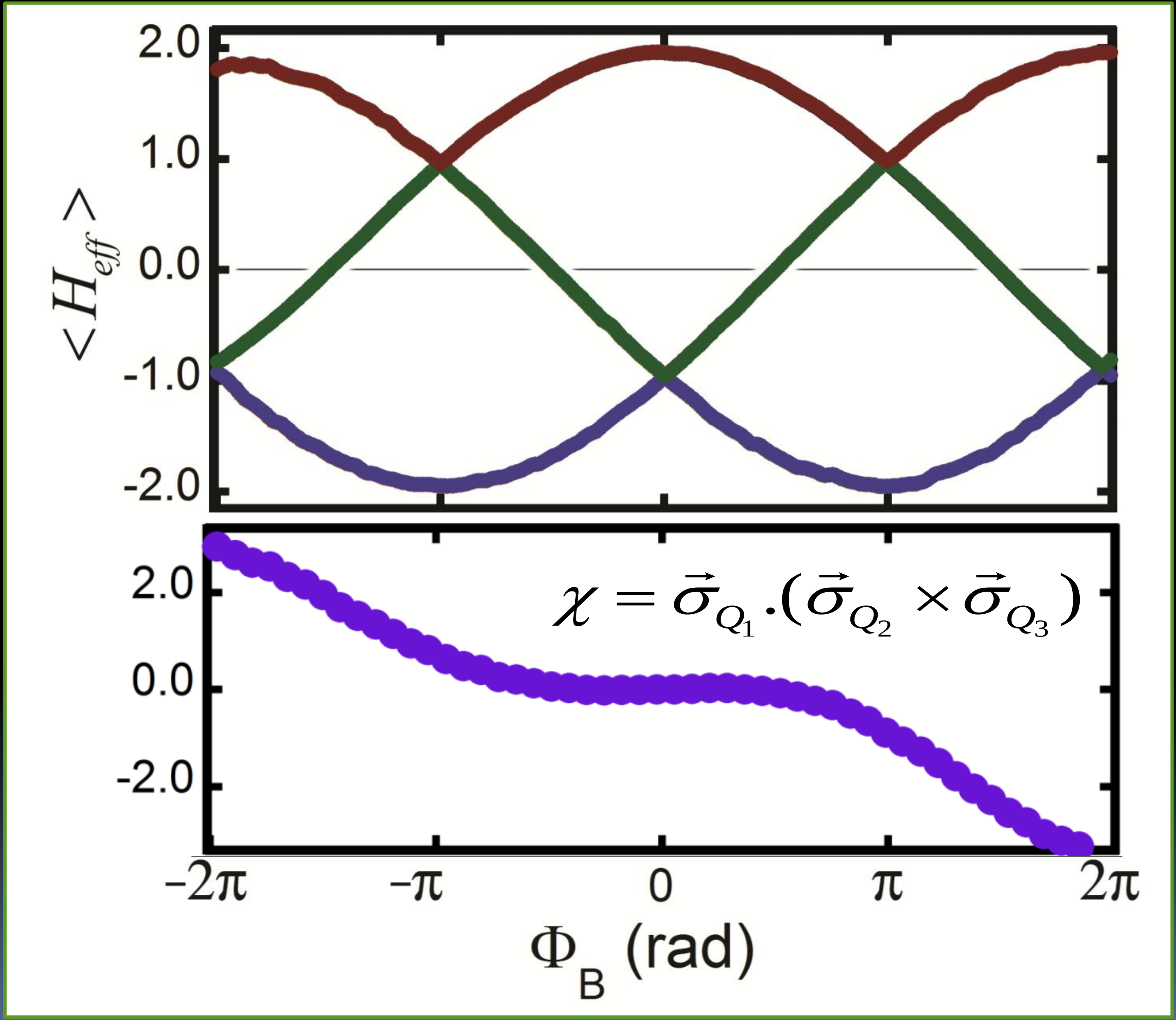
$$\psi_{\Phi_B} = \frac{e^{2i\Phi_B/3}|001\rangle + e^{i\Phi_B/3}|010\rangle + |100\rangle}{\sqrt{3}}$$

W-like state

$$E = \frac{1}{2}LI^2 = \frac{\Phi^2}{2L}$$

$$I = \frac{\partial E}{\partial \Phi}$$

Chirality

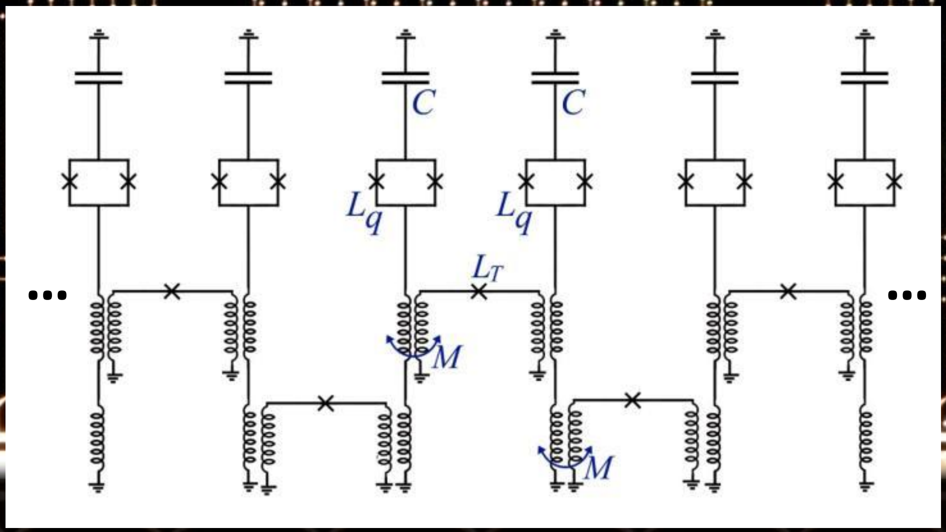


2.0
1.0
0.0
-1.0
-2.0
$< H_{eff} >$
$\chi = \vec{\sigma}_{Q_1} . (\vec{\sigma}_{Q_2} \times \vec{\sigma}_{Q_3})$
2.0
0.0
-2.0
−2π
−π
0
π
2π
Φ_B (rad)

$$H = \sum_{Qubits} h_x(t)\,\sigma^X + h_y(t)\,\sigma^Y + h_z(t)\,\sigma^Z + \sum_{j\neq k} g_{jk}(t)\,(a_j^{+} a_k + a_j a_k^{+})$$

At Google we are focusing on quantum computation
and
we are open to ideas

500$ vs.   500,000$



1 cm

An optical micrograph of the 9-qubit chip.

Google/UCSB quantum hardware team


Charles Neill

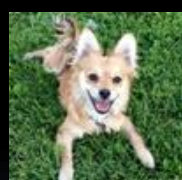

Anthony Megrant


Andrew Dunsworth


Michael Fang
(Caltech)

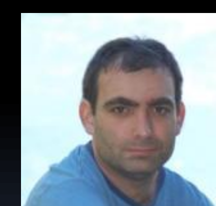

Prof. J. Martinis

qubit, lab mascot



Collaboration:

Tulane University


Prof. Eliot Kapit

ARMY RESEARCH OFFICE · NSF · IARPA · CNSI · UCSB

REUTERS EDITION: U.S.

HOME BUSINESS MARKETS WORLD POLITICS TECH OPINION BREAKINGVIEW

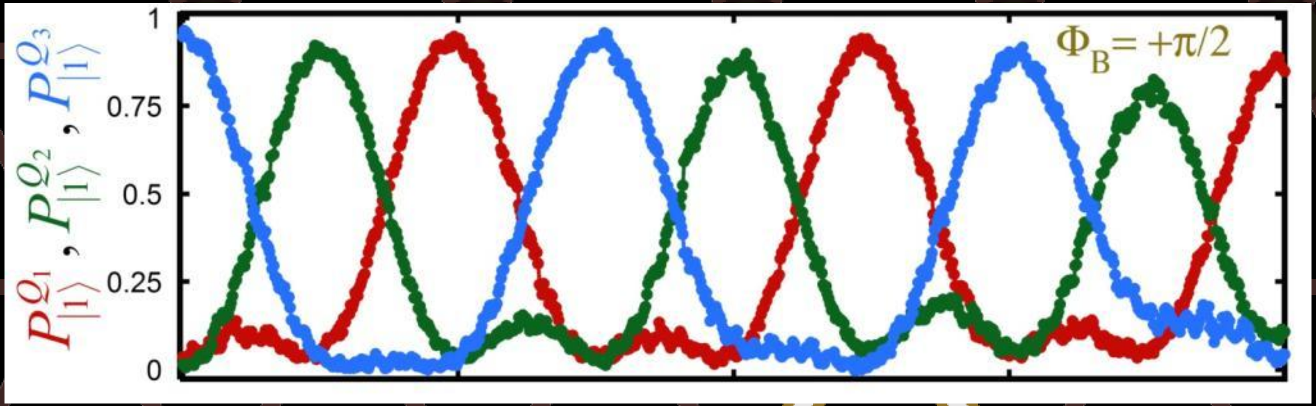
Google starts quantum computing research project

Tue Sep 2, 2014 10:47pm EDT

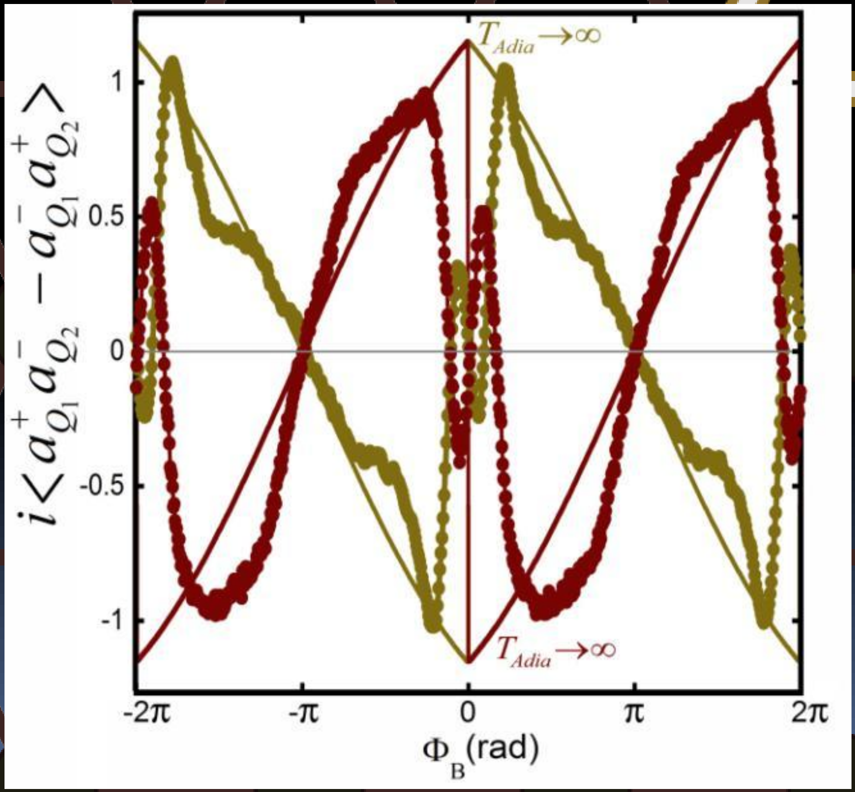
Tweet 58 Share 28 Share this 45 Email Print

Dr. Hartmut Neven

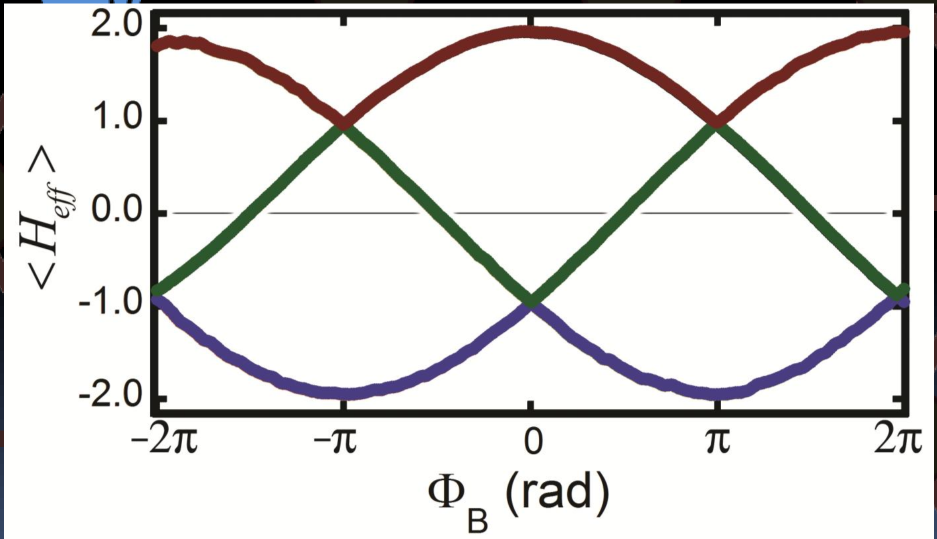
Conclusion



$P^{Q_1}_{|1\rangle}, P^{Q_2}_{|1\rangle}, P^{Q_3}_{|1\rangle}$
$\Phi_B = +\pi/2$
1
0.75
0.5
0.25
0



$i\langle a^+_{Q_1} a^-_{Q_2} - a^-_{Q_1} a^+_{Q_2} \rangle$
$T_{Adia} \to \infty$
$T_{Adia} \to \infty$
1
0.5
0
-0.5
-1
-2π
-π
0
π
2π
Φ_B(rad)



$\langle H_{eff} \rangle$
2.0
1.0
0.0
-1.0
-2.0
−2π
−π
0
π
2π
Φ_B (rad)