Quantum Information Science
with AMO

implementation …

- new AMO systems in lab → quantum info
- new “scenarios”

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A. Kantian
B. Kraus
I. Lesanovsky
A. Micheli
M. Müller
M. Ortner
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collaborations:
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H.P. Büchler (Stuttgart)
Jun Ye (JILA)
H.J. Kimble (Caltech)

SFB
Coherent Control of Quantum Systems

€U networks

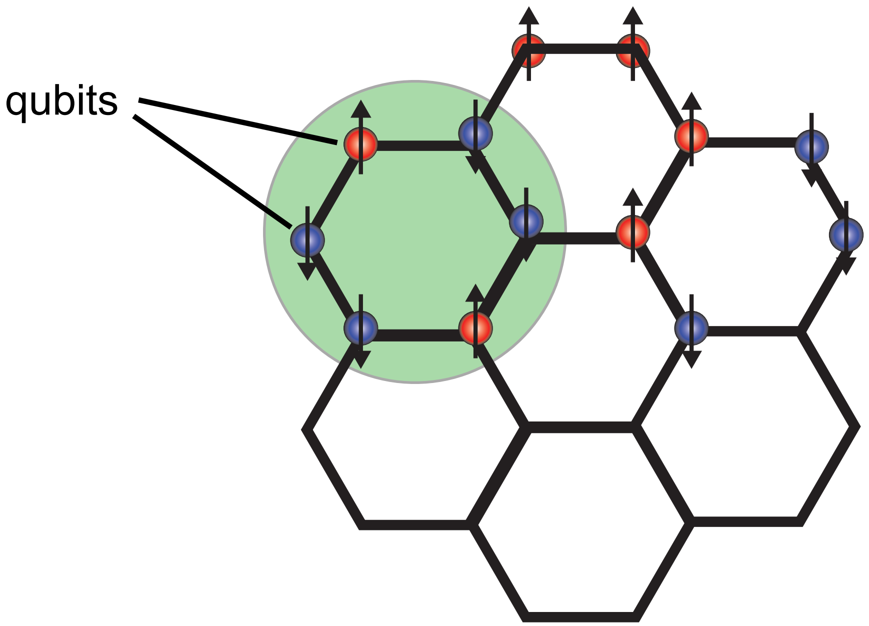
Topic 1:

Stuttgart + Innsbruck

(Stroboscopic) Coherent and Dissipative Quantum Simulations with Rydberg Atoms

(or: polar molecules / trapped ions)

“exotic” many body spin systems with many body interactions / constraints



- Generation of

$XXXXXX \qquad (X = \sigma_x)$

$ZZZZZZ$

... interactions or constraints

- Possible models: Kitaev toric code model, color codes, lattice gauge theories

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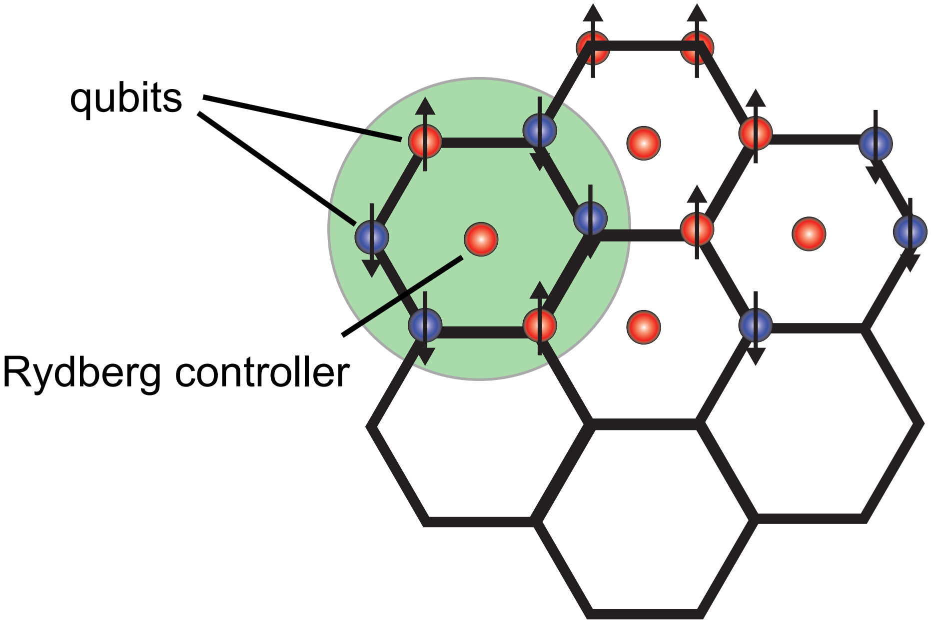

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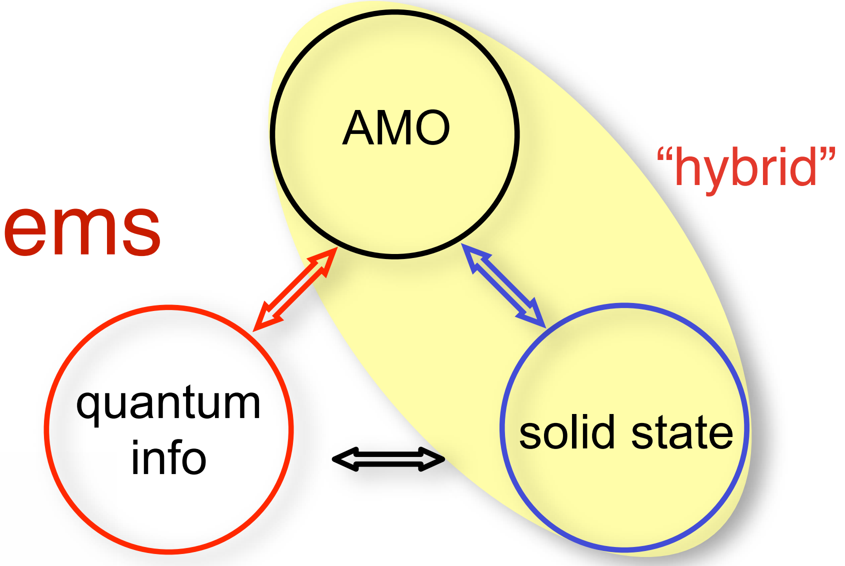
Topic 2:

AMO -Solid State Hybrid Systems



AMO

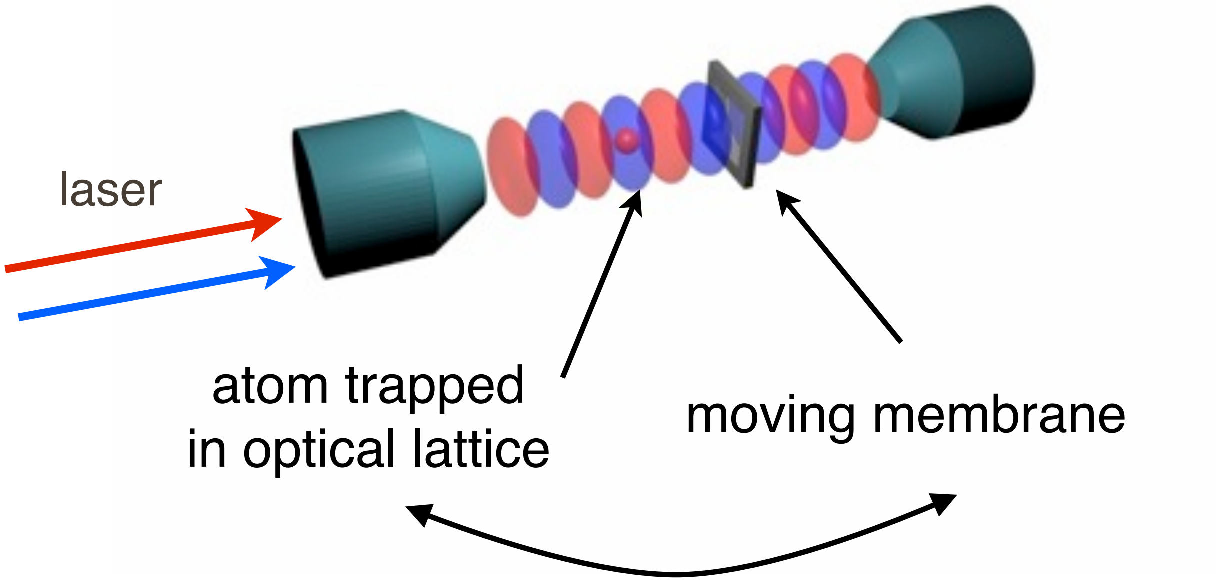
"hybrid"

quantum info

solid state

- strong coupling of single atom via photons to nanomechanical oscillator

see also M. Lukin's talk



laser

atom trapped in optical lattice

moving membrane

photons as quantum bus

Caltech + JILA + Innsbruck

Topic 1:
Quantum Simulations

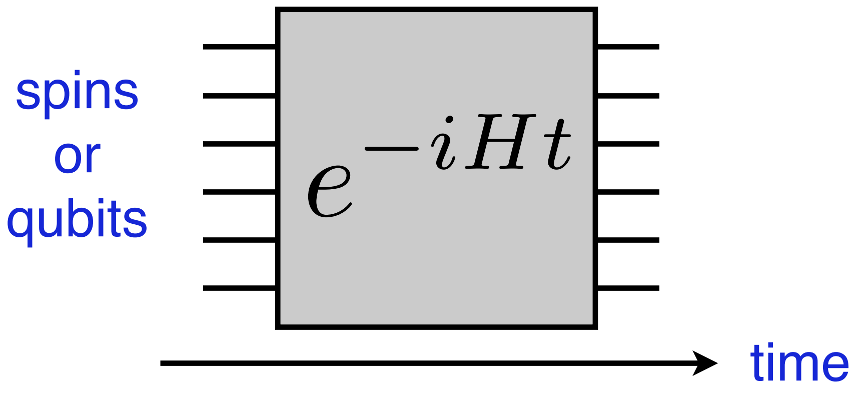
how?

- coherent & dissipative
- “analogue” & “digital” simulation

why?

- cond mat
- simulate exotic material
- prepare entangled state (as resource)

coherent many body dynamics

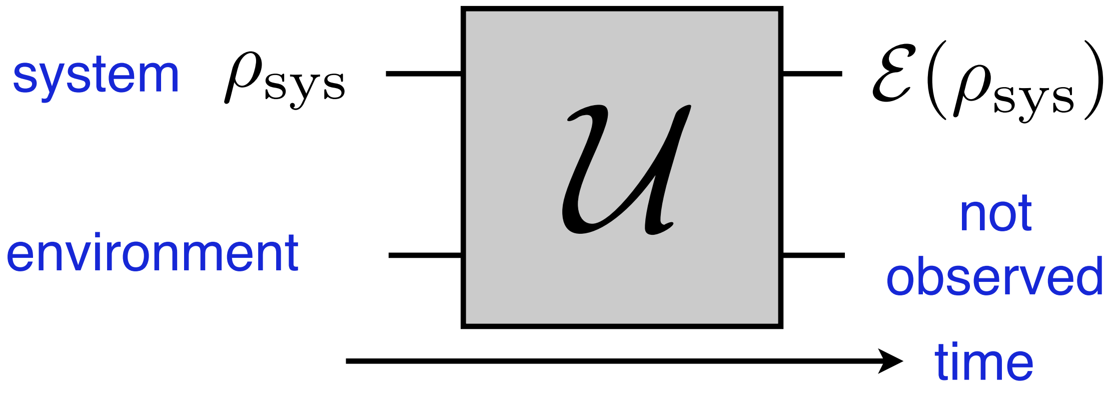


spins or qubits

e^{-iHt}

time

dissipative many body dynamics



system ρ_{sys}

environment

$\mathcal{U}$

$\mathcal{E}(\rho_{\text{sys}})$

not observed

time

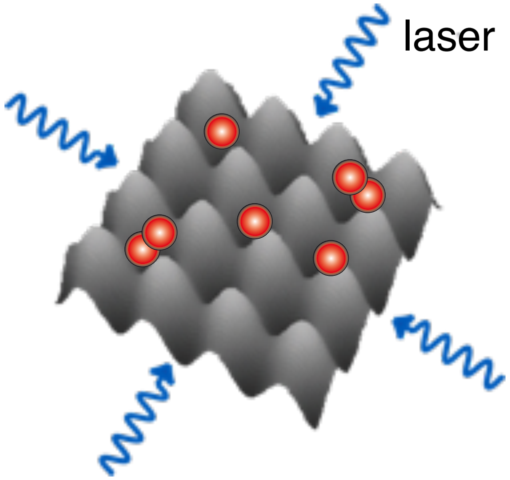
Feynman, Lloyd, ...

see talk by W. Phillips

Coherent Quantum Dynamics

- **“analogue” simulation**

optical lattice emulators



- We “build” a quantum system with desired dynamics & controllable parameters, e.g. Hubbard models of atoms in optical lattices
- [We know how to prepare (cool to) its ground state]

exp.: almost all cold atom labs, ...

It is <u>difficult</u> to mimic n-body interactions & constraints

$$\underset{\uparrow}{V^{(n)}} \sim \underset{\uparrow}{V^{(2)}} \frac{1}{E-H} \underset{\uparrow}{V^{(2)}} \dots V^{(2)} \frac{1}{E-H} V^{(2)} \rightarrow \text{"}0\text{"}$$

n-body

2-body

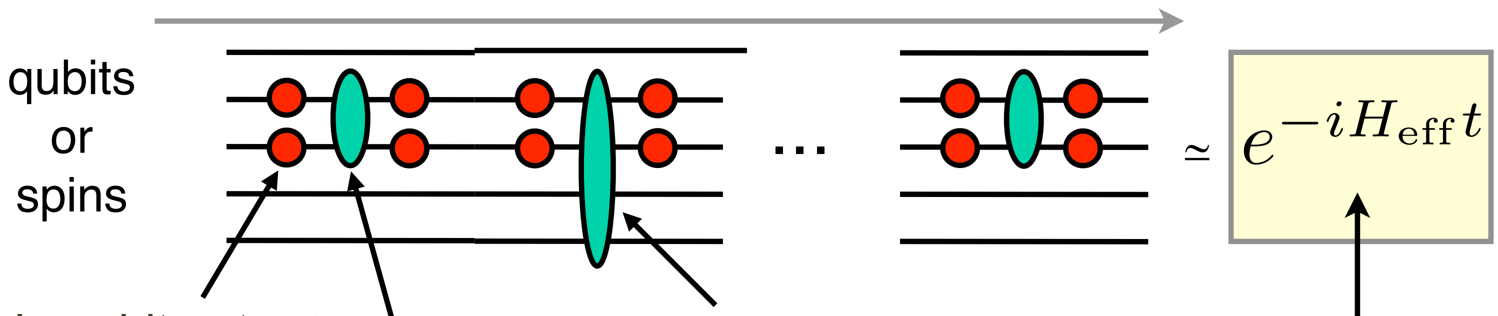
effective n-body interactions in perturbation theory

extended Hubbard models

Coherent Quantum Dynamics

- **“stroboscopic” or “digital” simulation**

stroboscopic time evolution as
sequence of quantum gates



time

qubits
or
spins

$$\simeq e^{-iH_{\text{eff}}t}$$

single qubit gate

2-qubit gate

n-qubit gate ~ n-body interaction

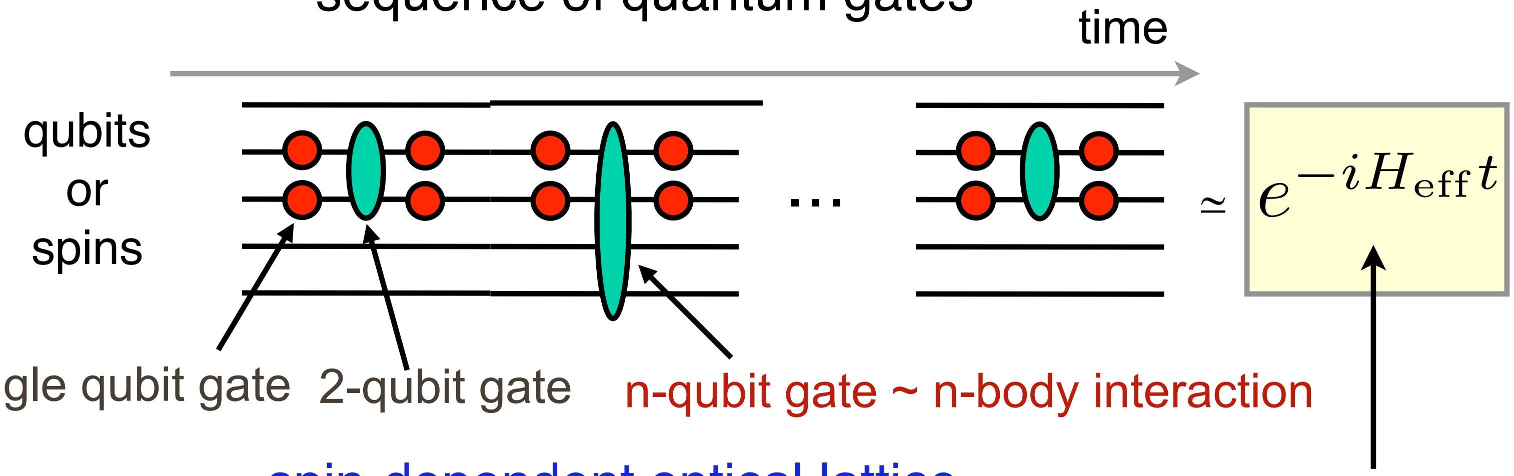
Lloyd, ...

desired many body Hamiltonian
“on the average”
Q.: errors?

Coherent Quantum Dynamics

- **“digital” simulation**

stroboscopic time evolution as sequence of quantum gates



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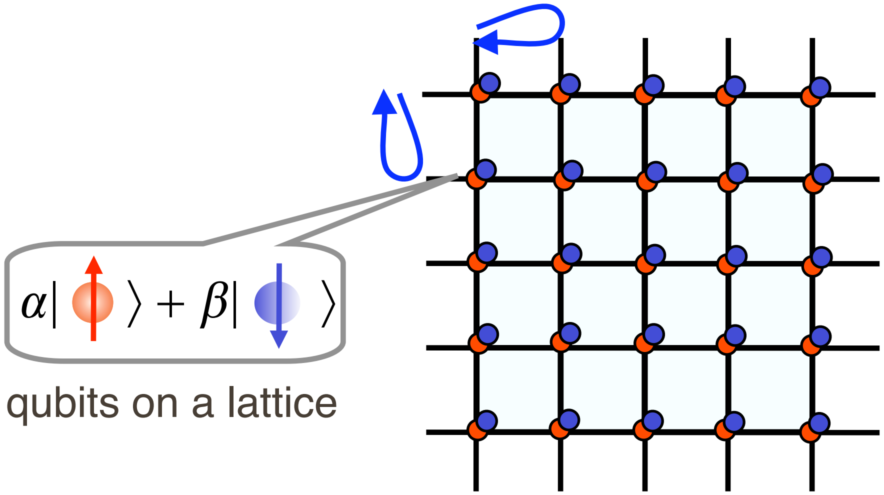
spin-dependent optical lattice



qubits on a lattice

entangling qubits via "Ising"
(cluster state)

exp.: Bloch, Meschede, ...

Coherent Quantum Dynamics

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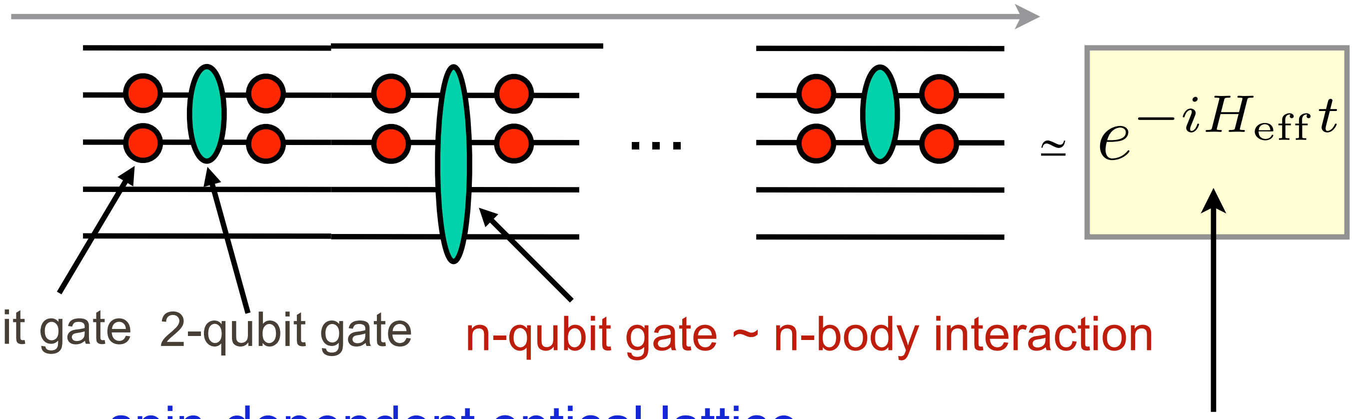

single qubit gate 2-qubit gate n-qubit gate ~ n-body interaction

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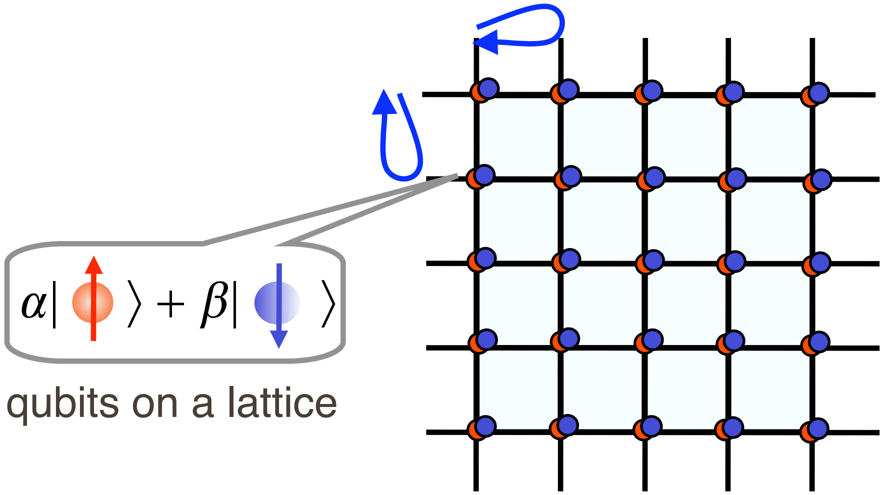

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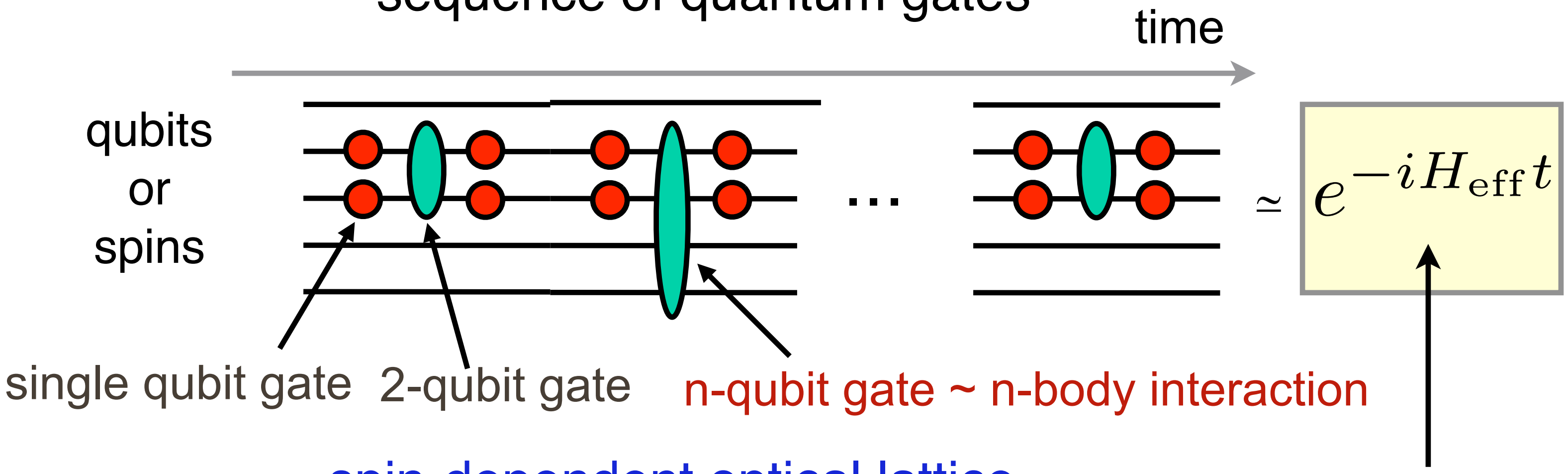

$\simeq$ $e^{-iH_{\mathrm{eff}}t}$

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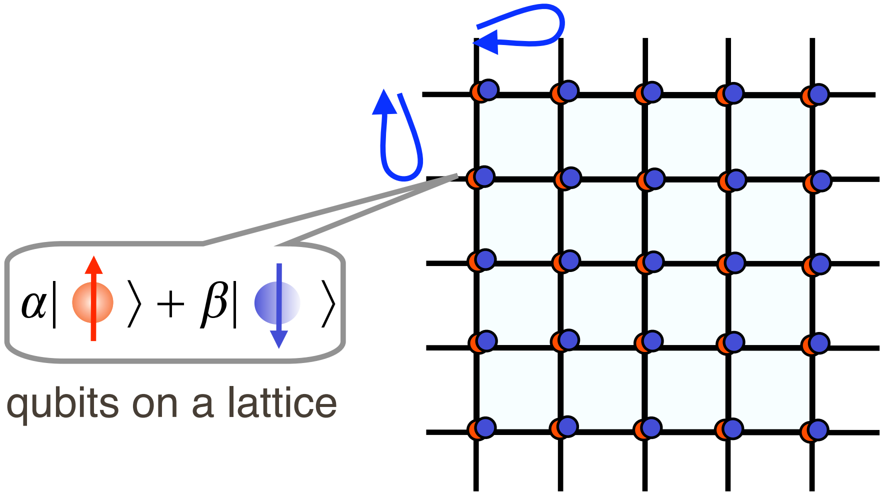

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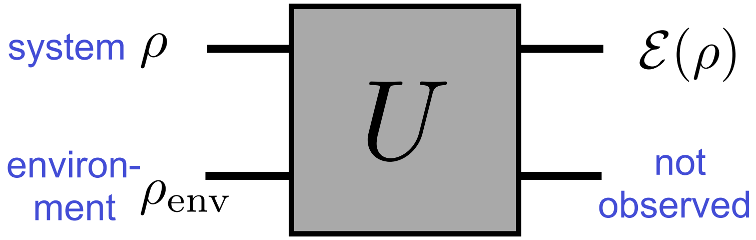
B. Kraus et al., PRA 2008
S. Diehl et al. Nature Physics 2008
[see also: Verstraete, Cirac et al. 2008]

Open Quantum Systems

- **Q.: dissipative preparation of entangled states**



$$\rho \longrightarrow \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

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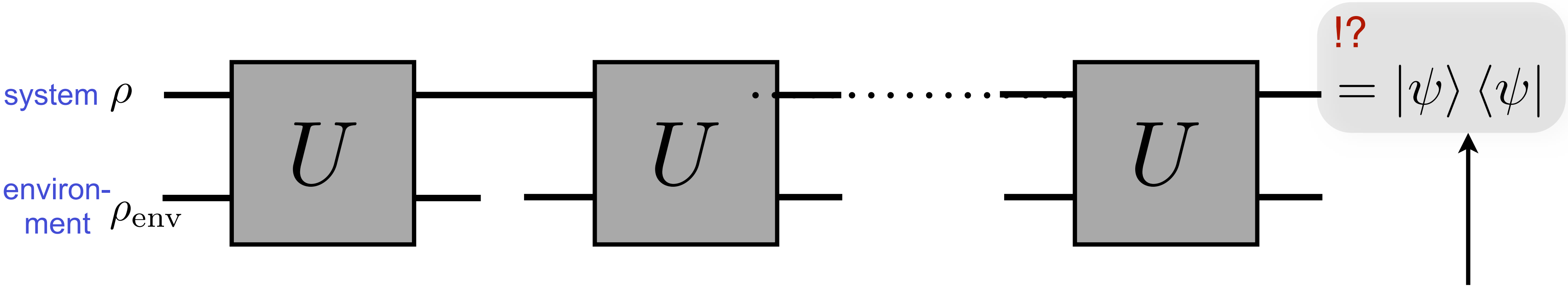

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engineer coupling to a quantum reservoir

pumping into *pure* entangled state of interest

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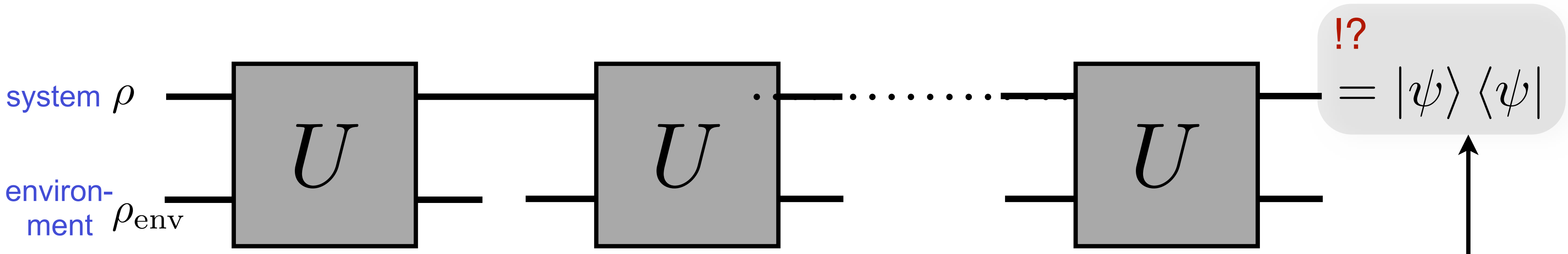

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engineer coupling to
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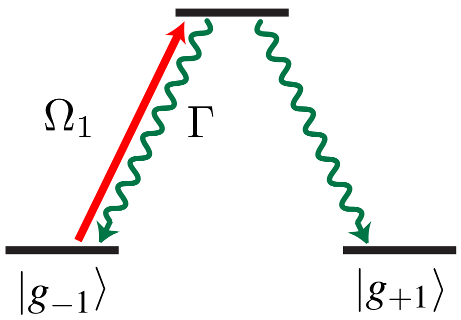
- **optical pumping (Kastler) or laser cooling**



$$\rho(t) \xrightarrow{t\rightarrow\infty} |g_+\rangle\langle g_+|$$

driven dissipative dynamics
"purifies" the state

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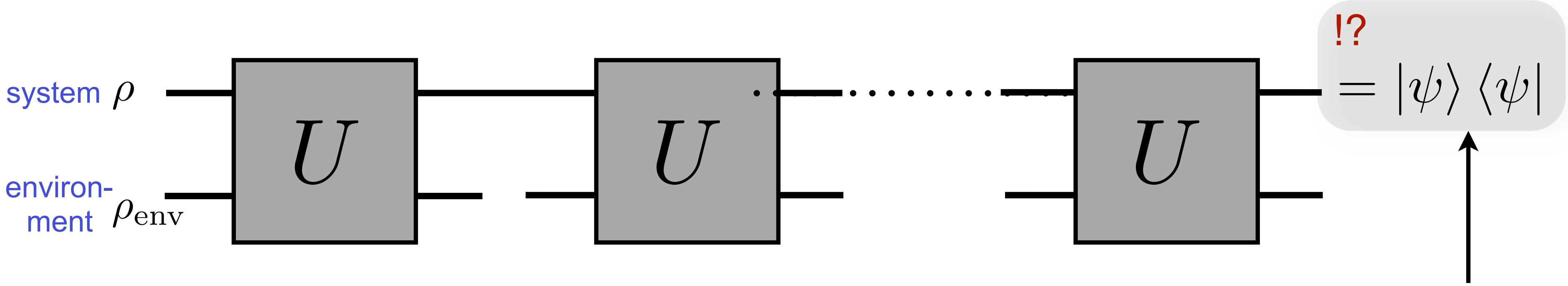

$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

n-body quantum jump operators ☹

engineer coupling to
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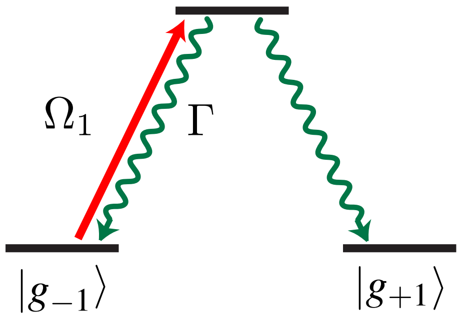

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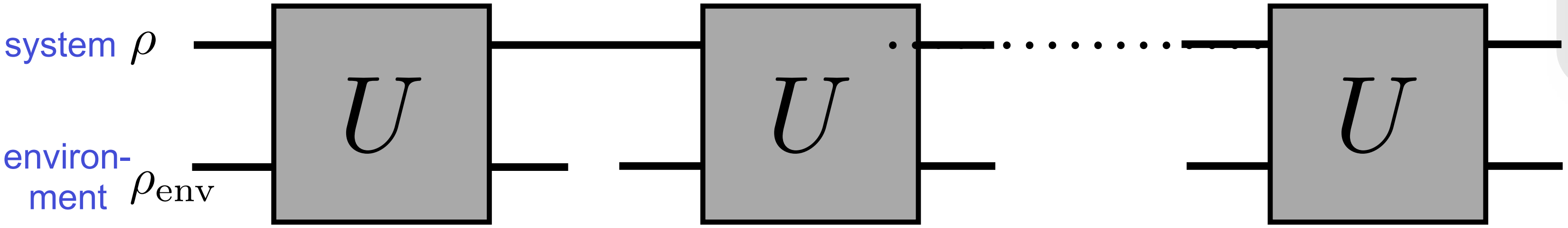
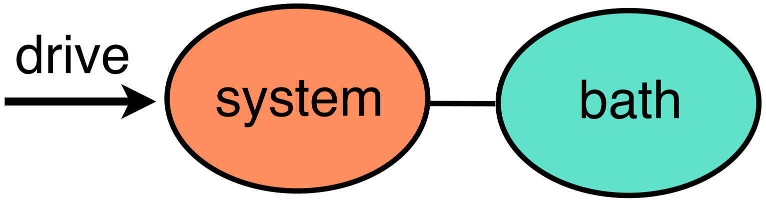


$$\overset{!?}{=} |\psi\rangle\langle\psi|$$

pumping into *pure* entangled state of interest

$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

- **Lindblad master equation**



$$\frac{d\rho}{dt} = -i\,[H,\rho] + \mathcal{L}\rho$$

$$\rho(t) \xrightarrow{t\to\infty} \rho_{ss}$$

mixed state

$$\overset{!?}{=} \quad |D\rangle\langle D|$$

pure state ("dark state")

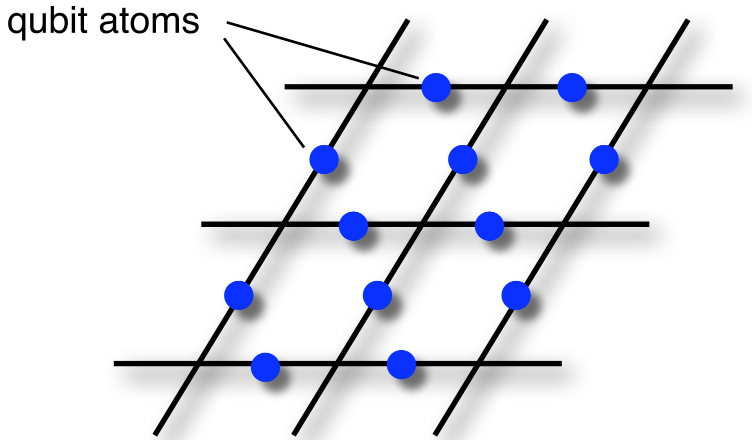
steady state

Q.: engineer quantum reservoirs couplings?

n-body quantum jump operators ☹

Example: Kitaev Toric Code

- **Kitaev**



- toric code $|K\rangle$ with $\left\{S_x^{(p)}|K\rangle = |K\rangle, S_z^{(s)}|K\rangle = |K\rangle\right\}$ for all X and Z stabilizers
- ground state of the Kitaev toric code Hamiltonian

$$\begin{aligned} H &= -h \sum_{\text{plaquette}} \sigma_x^{(1_p)}\sigma_x^{(2_p)}\sigma_x^{(3_p)}\sigma_x^{(4_p)} - h \sum_{\text{star}} \sigma_z^{(1_s)}\sigma_z^{(2_s)}\sigma_z^{(3_s)}\sigma_z^{(4_s)} \\ &= -h \sum_p S_x^{(p)} - h \sum_s S_z^{(s)} \end{aligned}$$

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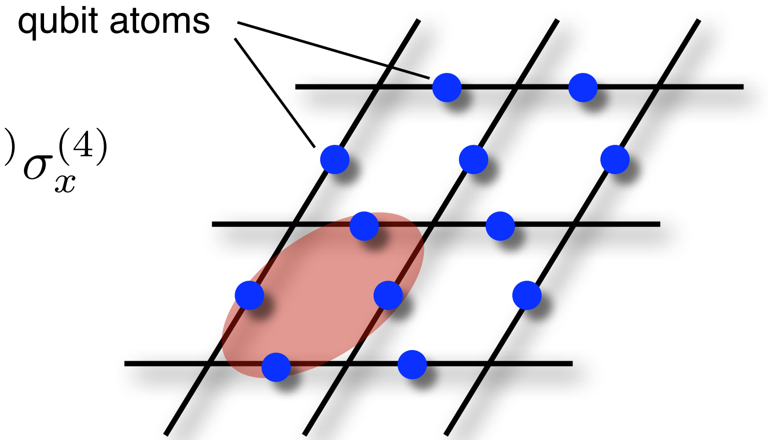

four body interaction $S_x = \sigma_x^{(1)}\sigma_x^{(2)}\sigma_x^{(3)}\sigma_x^{(4)}$

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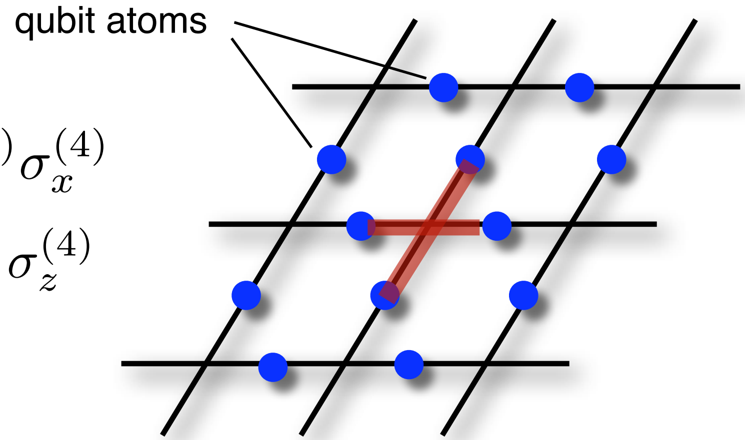

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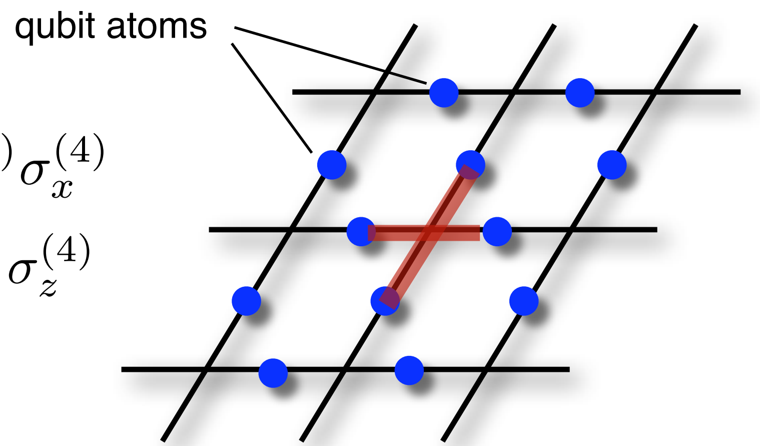

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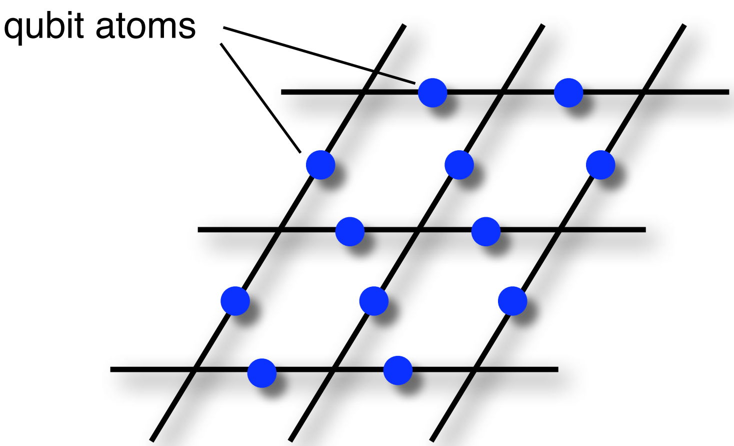
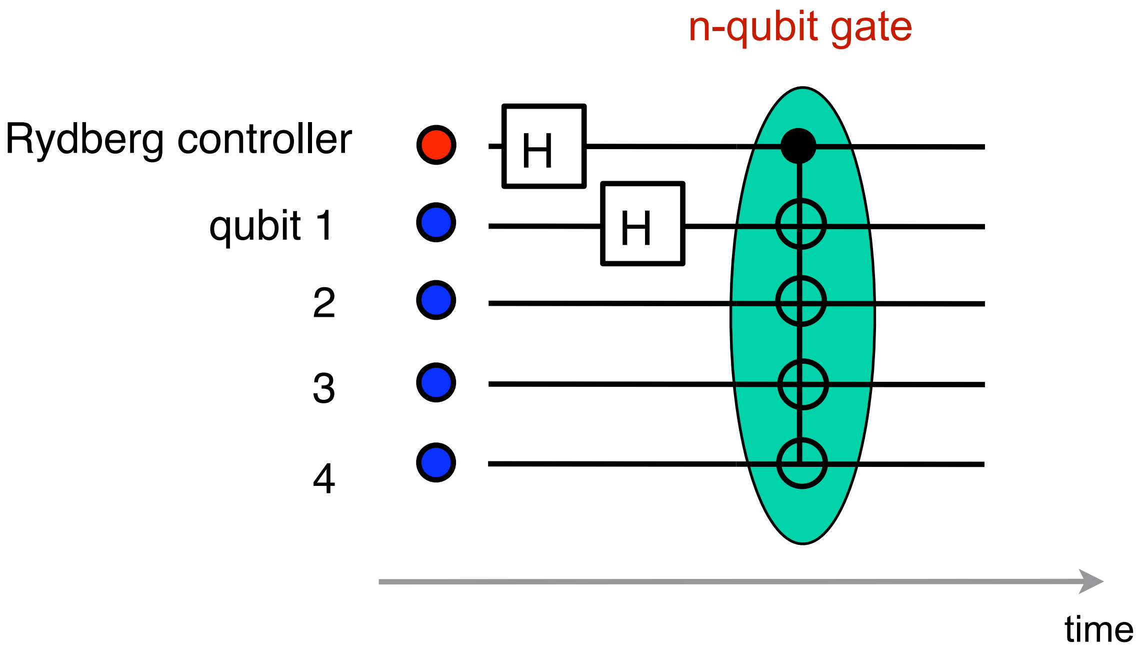
- Q.: can we simulate the toric code 4-body Hamiltonian?
- Q.: can we prepare the ground state dissipatively?

with Rydberg atoms
& dipolar interactions

Example: Kitaev Toric Code

- **Rydberg implementation**





Example: Kitaev Toric Code

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four-body interaction term
via Rydberg dipole-dipole

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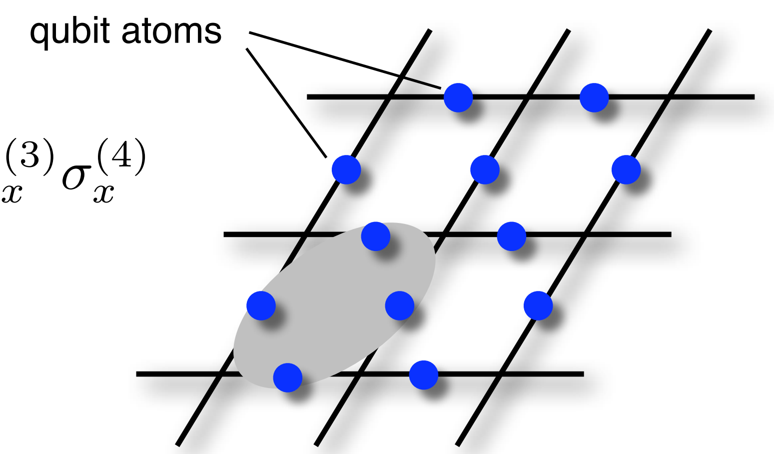

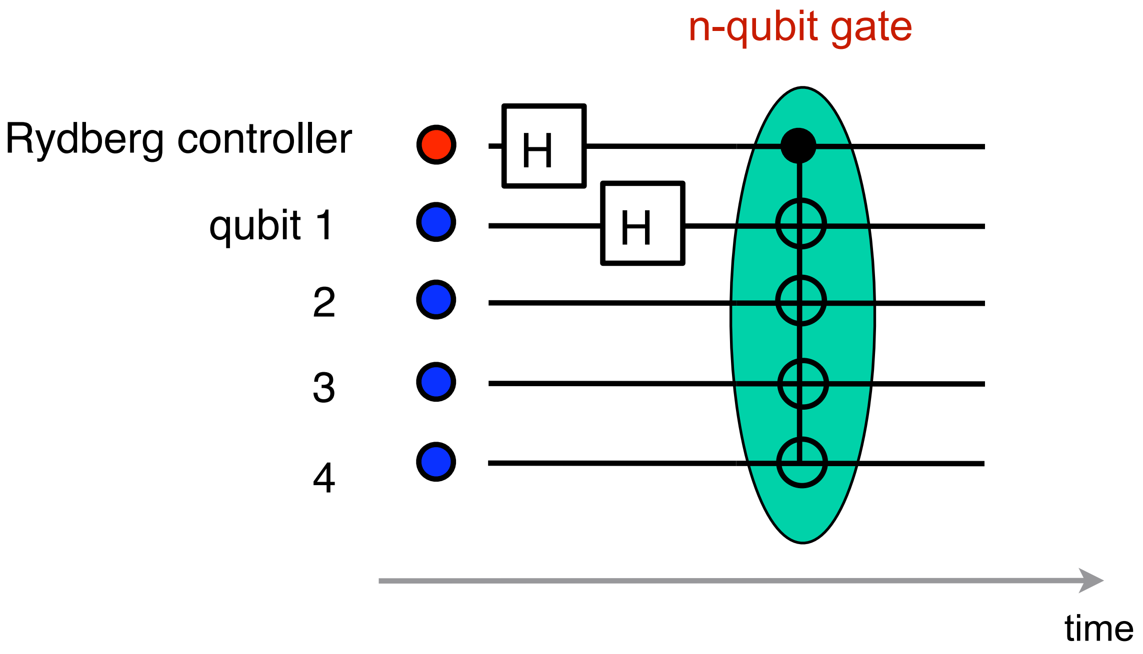

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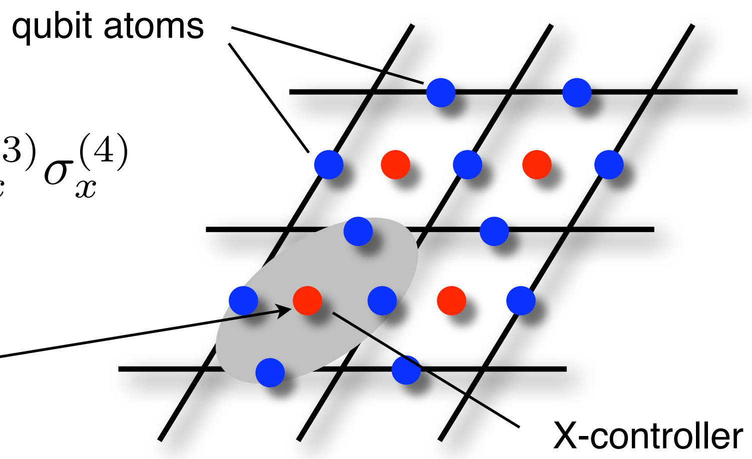
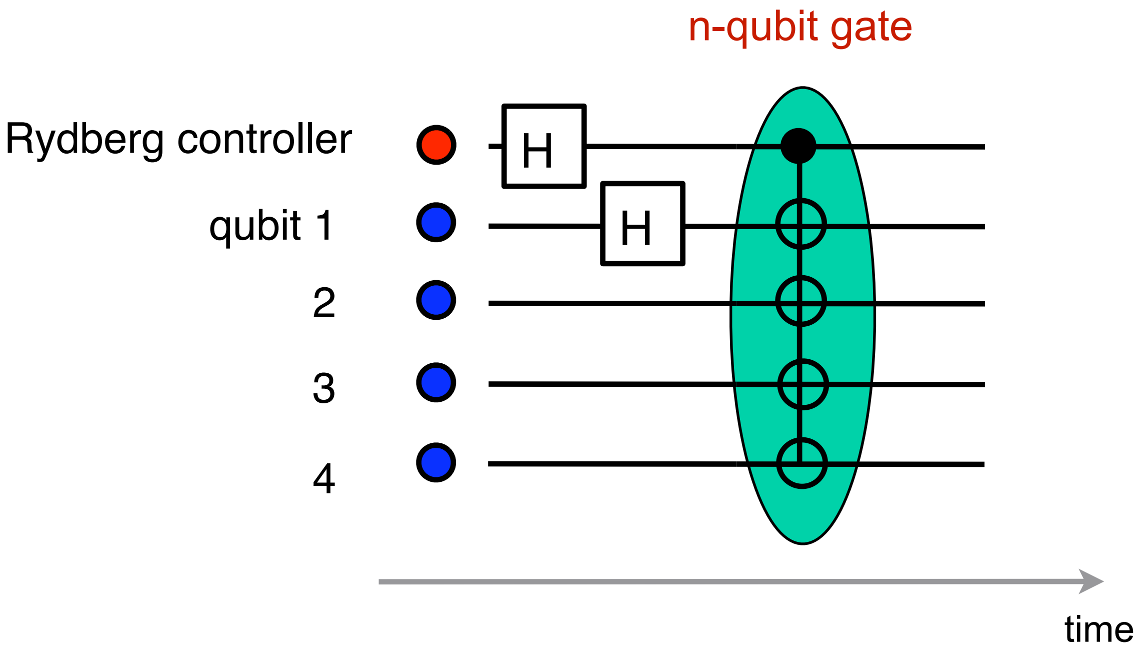
... can be simulated with help of
an auxiliary X-controller atom





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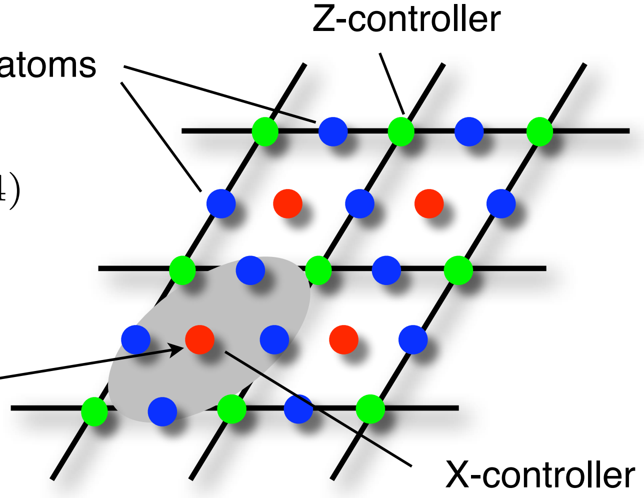

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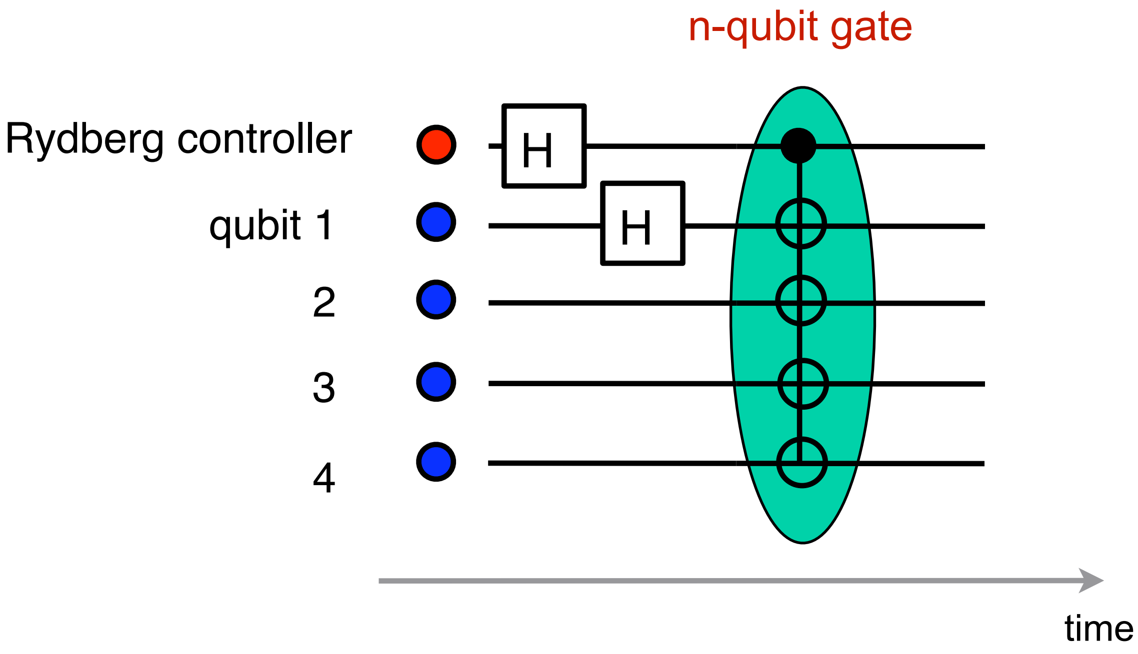
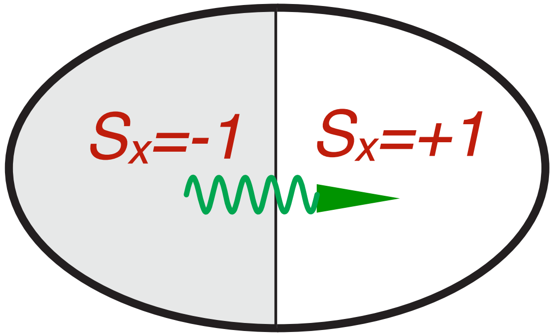
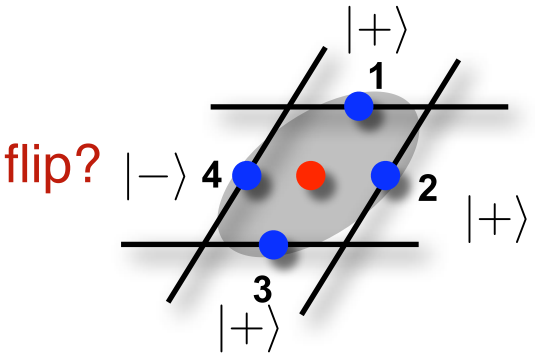


Example: Kitaev Toric Code

- **pumping stabilizer states**





$$T_x : \rho_s \mapsto A_1 \rho_s A_1^\dagger + A_2 \rho_s A_2^\dagger$$

$$A_1 = \frac{1}{2}(1 - S_x) = A_1^\dagger \qquad A_2 = \frac{1}{2}\sigma_z^{(i)}(1 + S_x) \neq A_2^\dagger$$

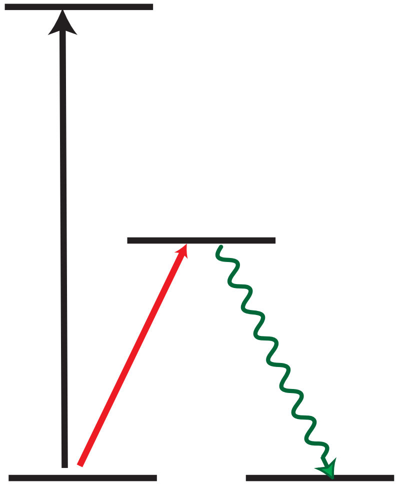
if +1, do nothing

if -1, pump

$$\sigma_x |\pm\rangle = \pm |\pm\rangle$$

4 & 5 body operators ☹

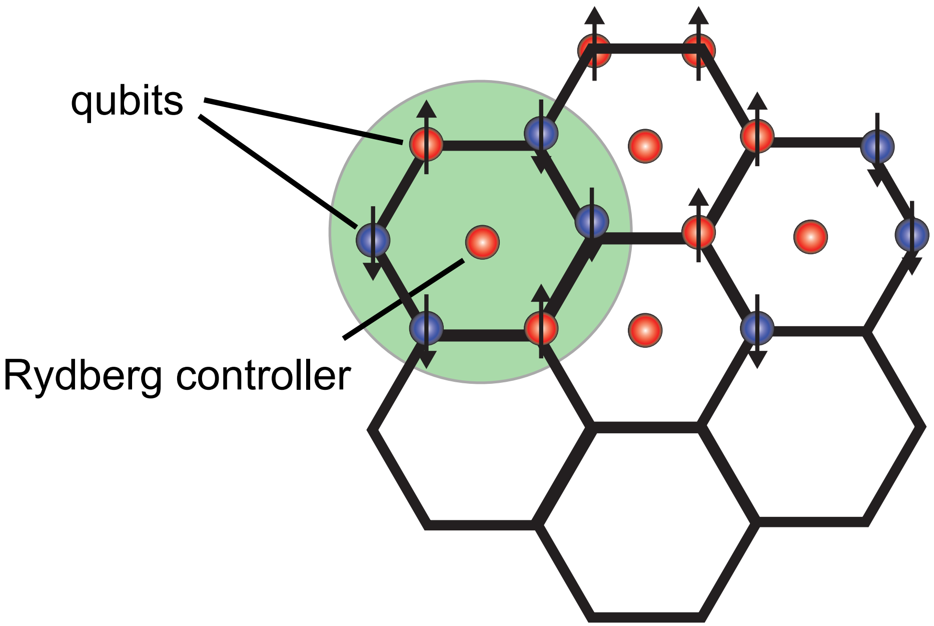
- **n-qubit gate + optical pumping of the Rydberg atom**



Müller et al, PRL 2009

Building Block: n-qubit CNOT Rydberg Gate

- **gate: ingredients**
  - atoms in a large spacing optical lattice: addressability [D. Weiss]
  - Rydberg dipole-dipole



features:

✓ High fidelity even for moderately large # qubits

✓ Fast 3 laser pulses

✓ Long-range interactions

✓ Robust with respect to
  - inhomogeneities in the interparticle distances
  - variations in the interaction strengths
  - no mechanical effects

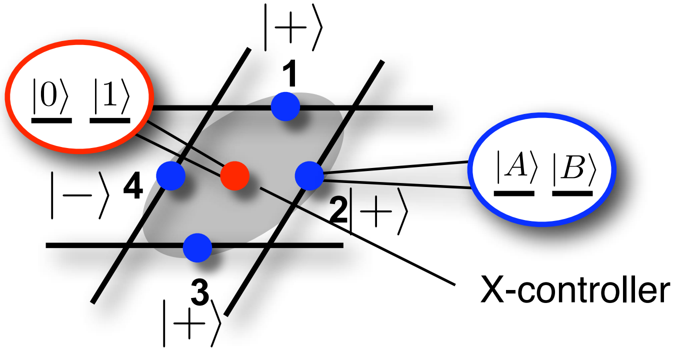
✓ experimentally realistic parameters

$$G = |0\rangle_c\langle 0| \otimes 1 + |1\rangle_c\langle 1| \otimes \underbrace{\sigma_x^{(1)}\sigma_x^{(2)}\sigma_x^{(3)}\sigma_x^{(4)}}_{\text{n-qubits}} \ldots$$

Rydberg controller

dark state magic

1. Coherent Time Step



resource:
our multi-qubit CNOT-gate

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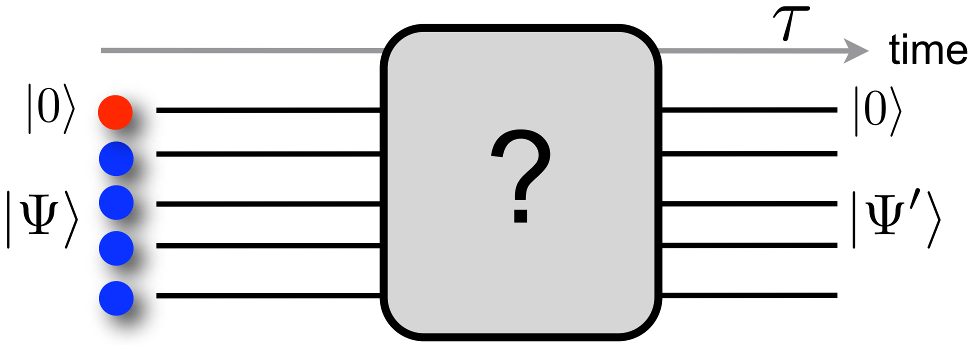

- composed evolution $|\Psi'\rangle = U|\Psi\rangle$

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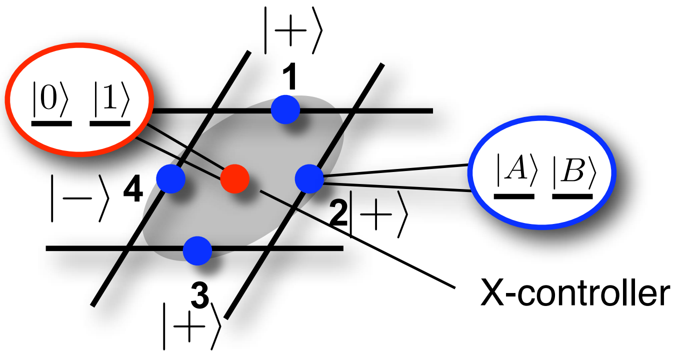
with

$$H = -\frac{\hbar\alpha}{\tau}\sigma_x^{(1)}\sigma_x^{(2)}\sigma_x^{(3)}\sigma_x^{(4)}$$

- stroboscopic simulation
- … and similar for *ZZZZ*

1. Coherent Time Step



our multi-qubit CNOT-gate

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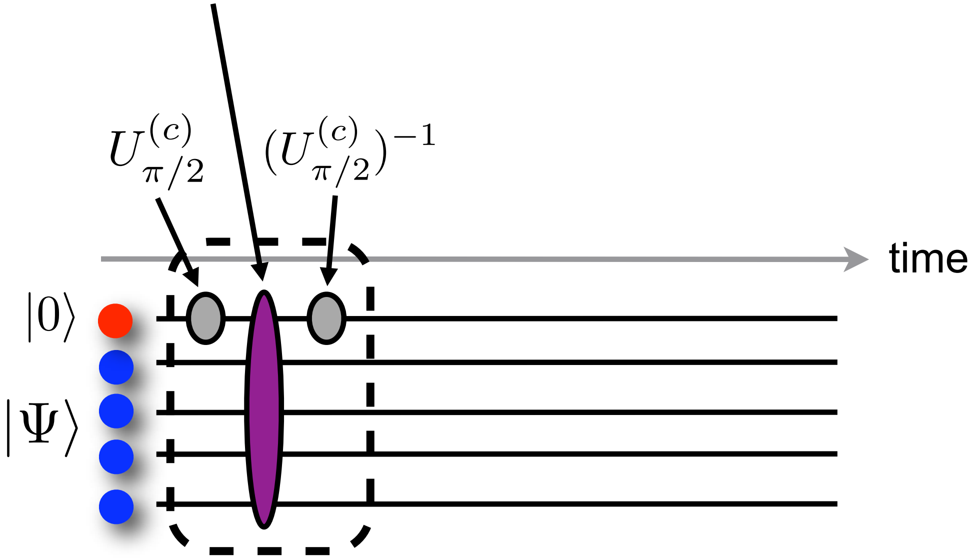

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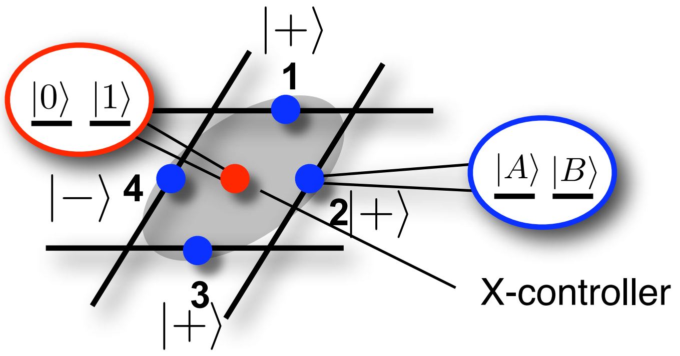

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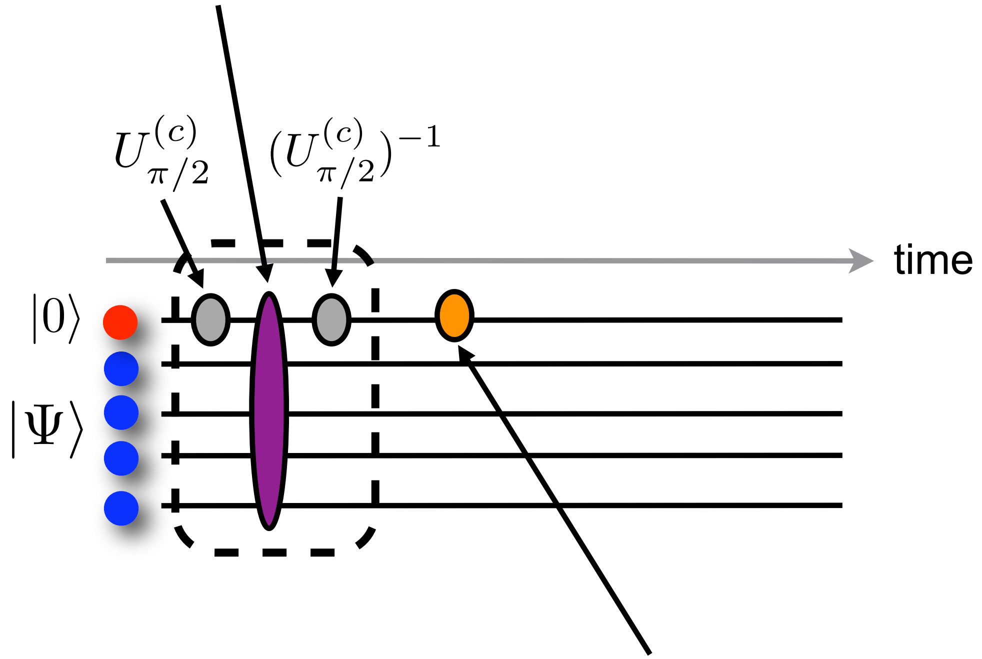

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small local rotation of the control atom

$$\alpha \ll 1$$

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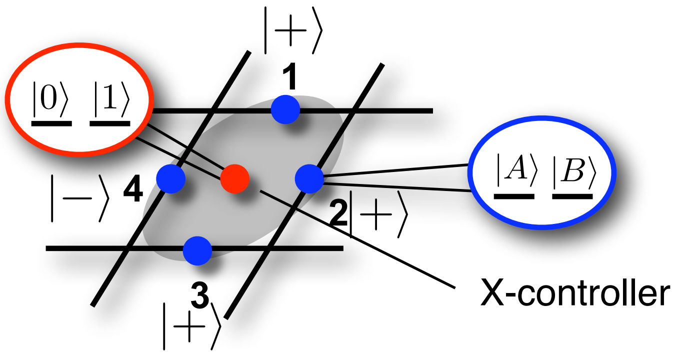

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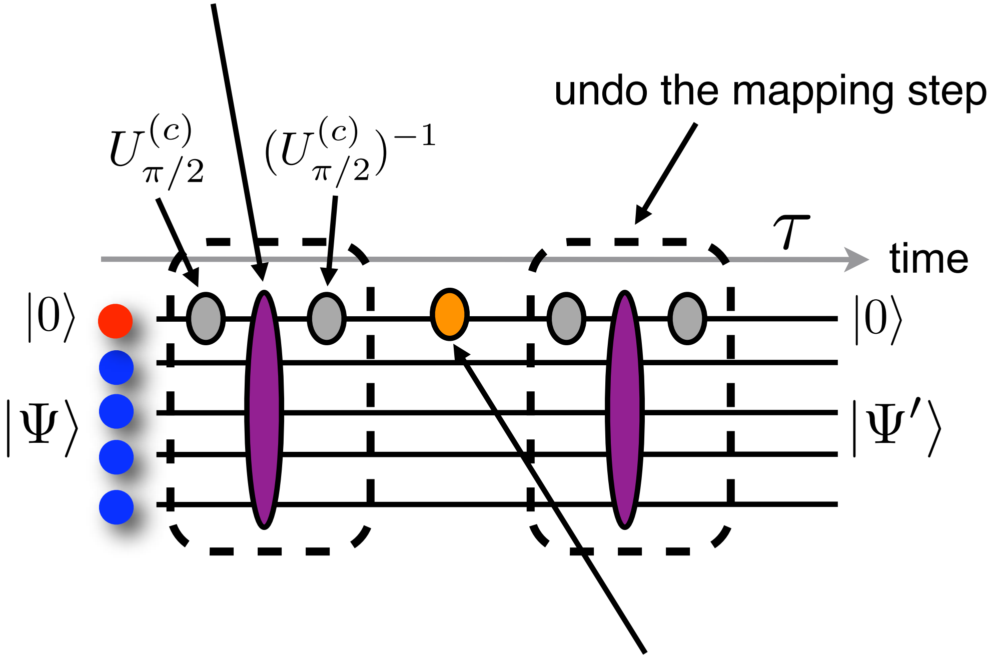

undo the mapping step

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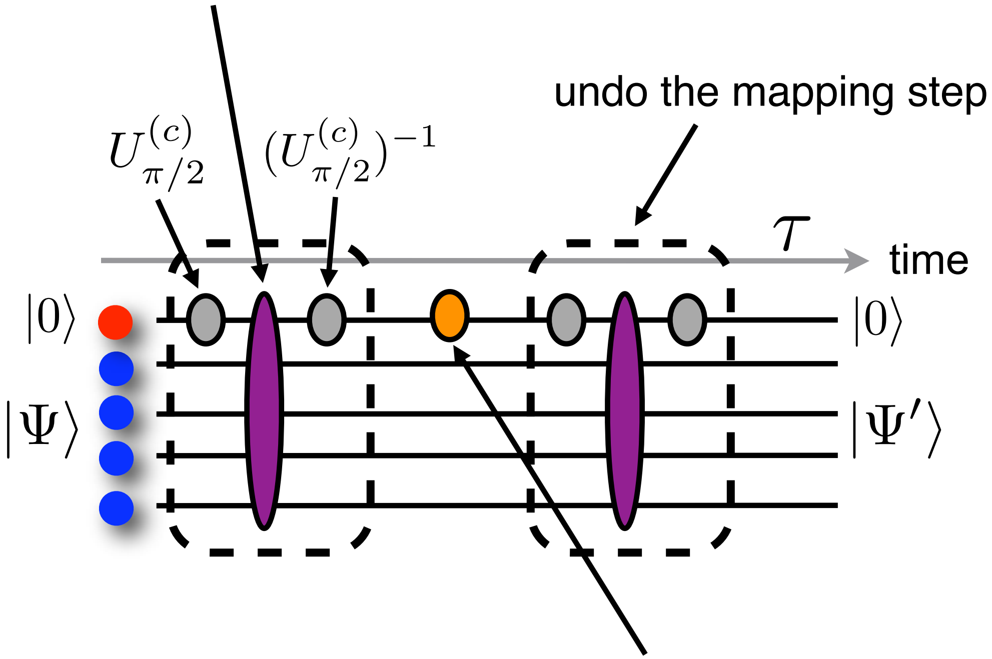

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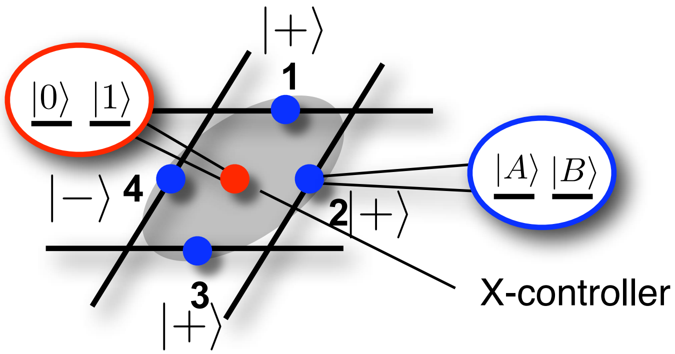

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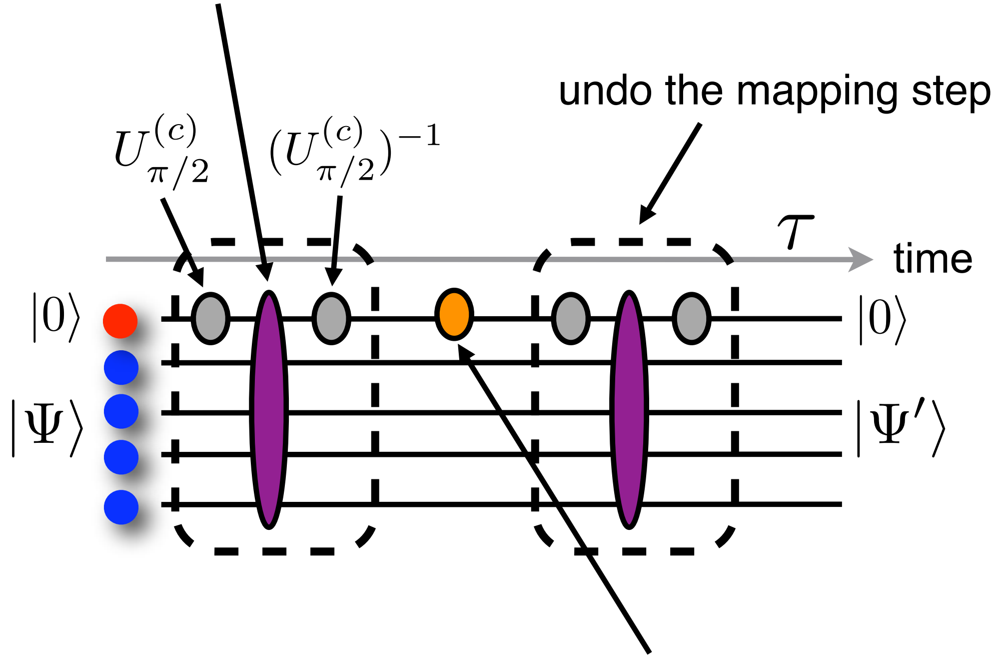

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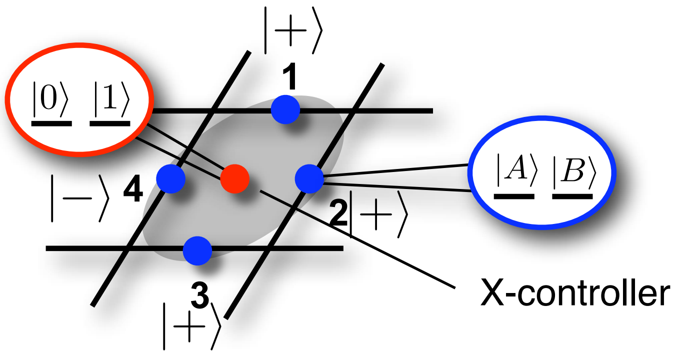

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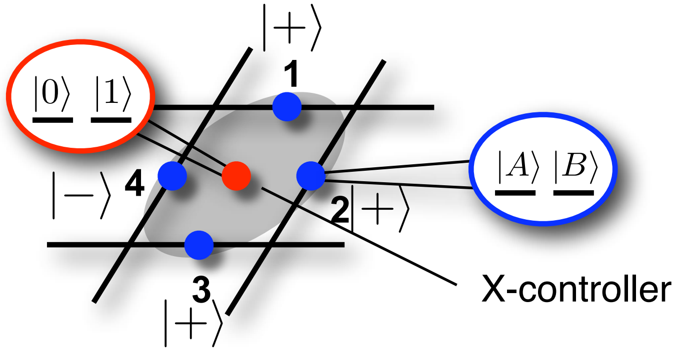
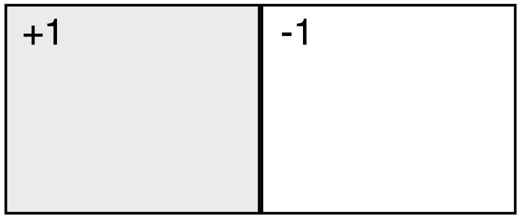
- stroboscopic simulation
- energy scale set by rotation angle α and gate duration τ

2. Dissipative Step

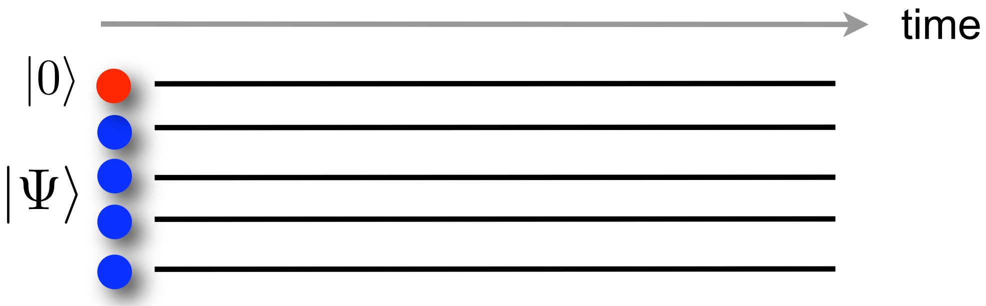
- map the eigenvalue information onto the controller



$$S_x|\Psi\rangle = +1|\Psi\rangle \qquad S_x|\Psi\rangle = -1|\Psi\rangle$$



Hilbert space of the four spins



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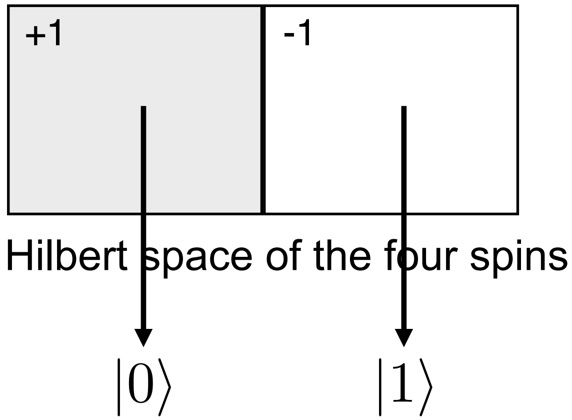

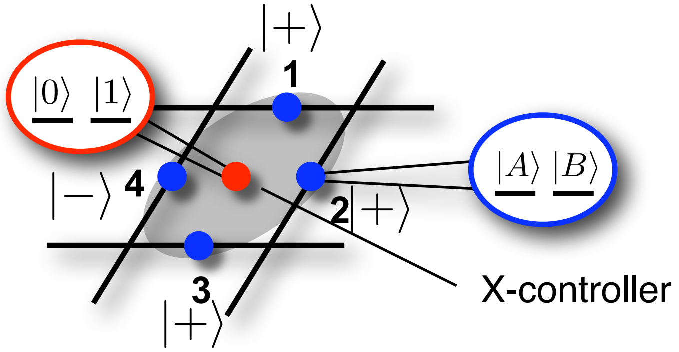

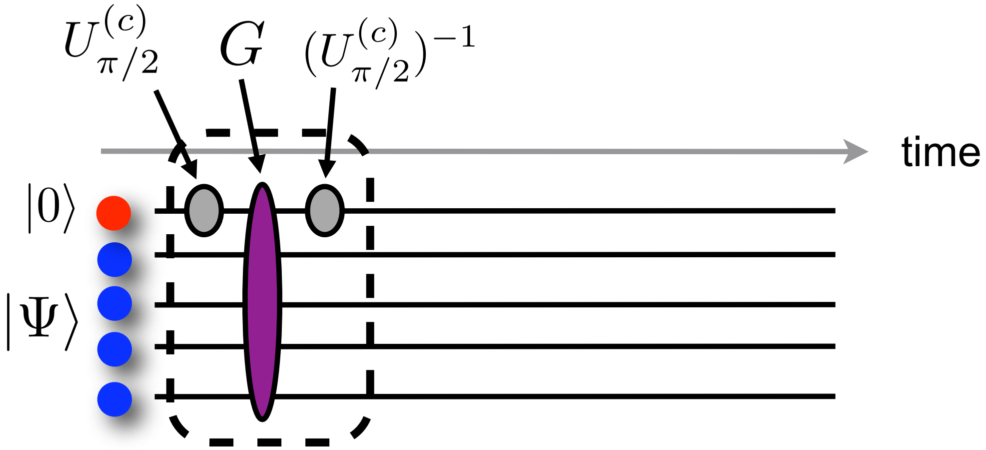

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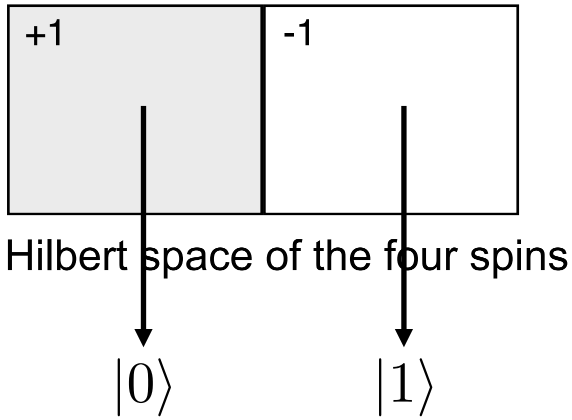
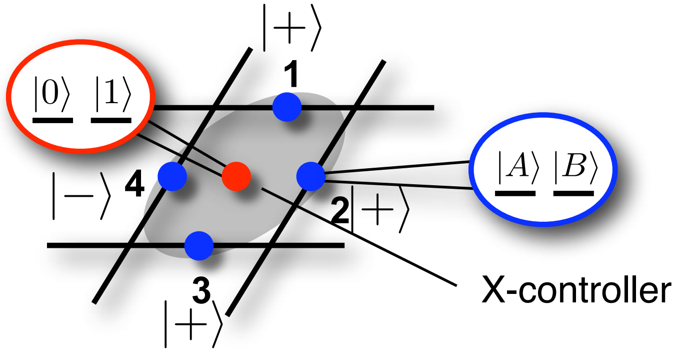
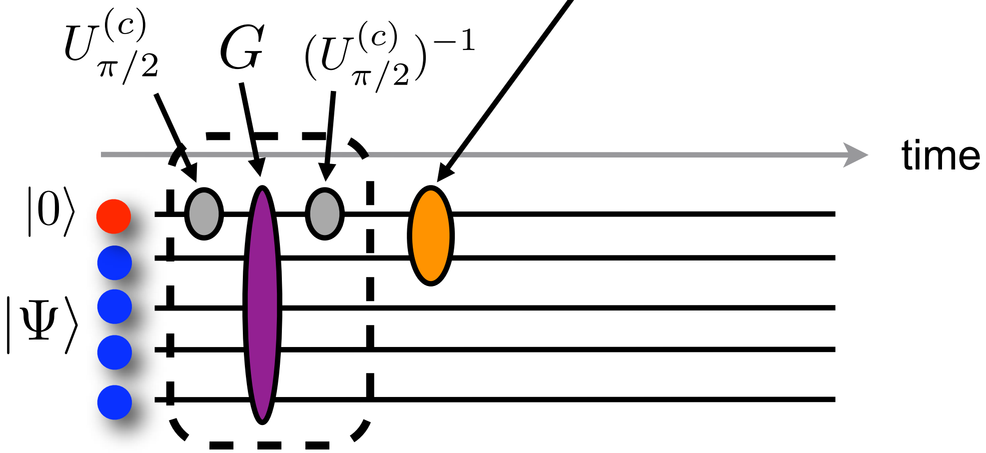




- conditional spin flip of one qubit

$$C = |0\rangle_c\langle 0| \otimes 1 + |1\rangle_c\langle 1| \otimes \exp(i\phi\sigma_z^{(1)})$$



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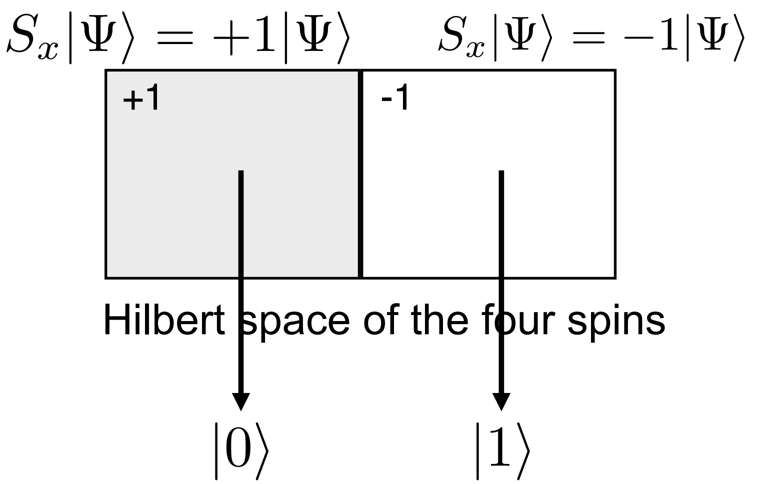

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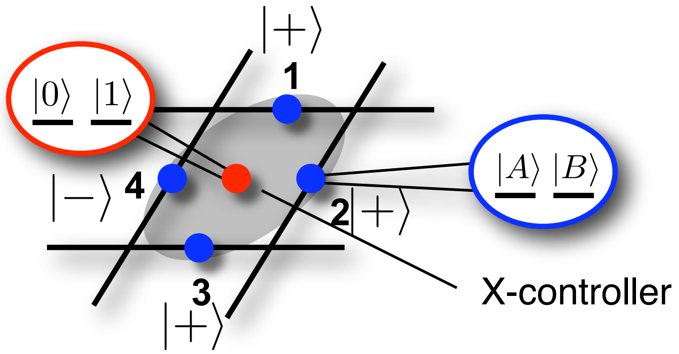

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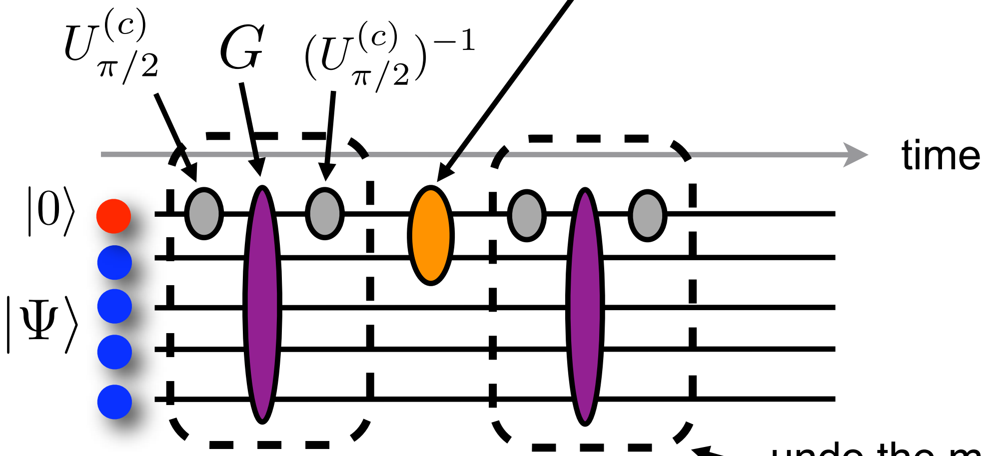

undo the mapping step

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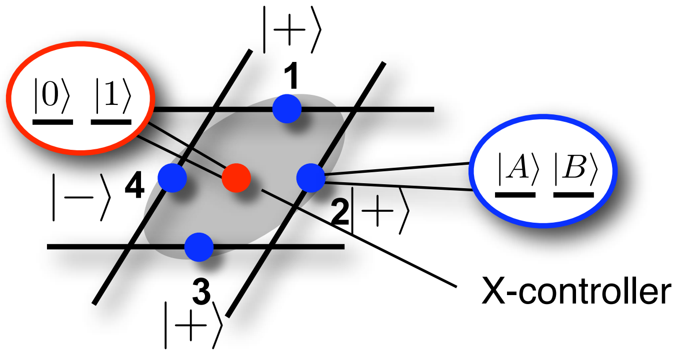

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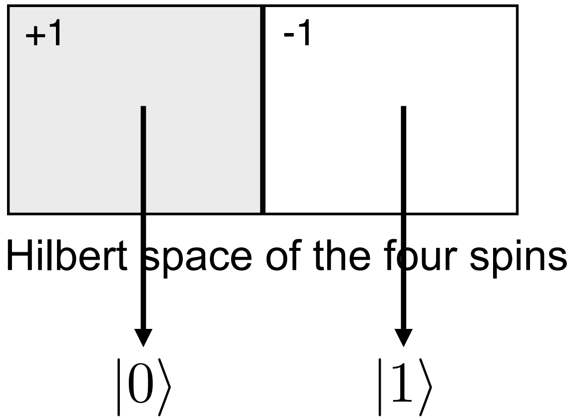

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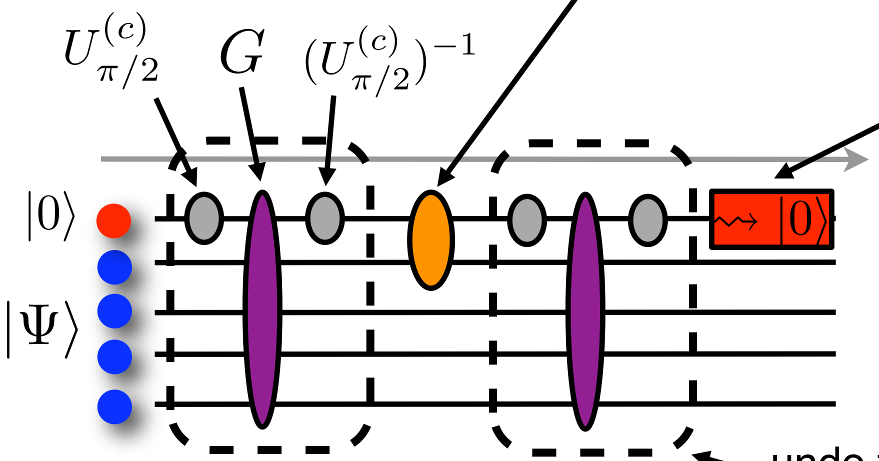


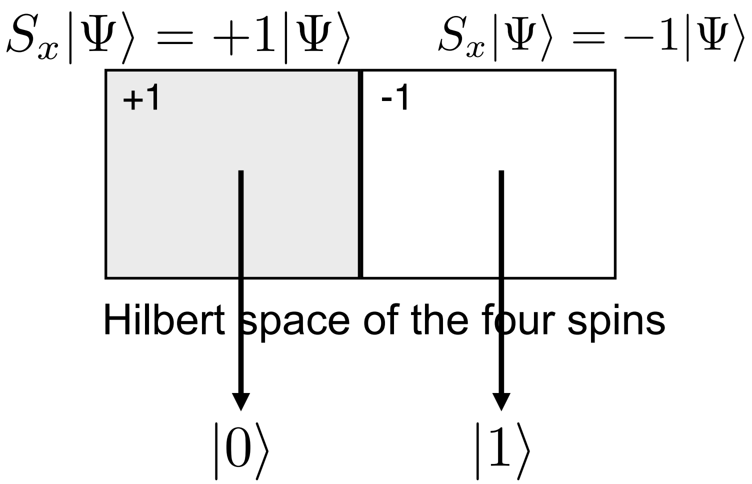
dissipative step: optical pumping of the control atom

time

undo the mapping step

2. Dissipative Step

- map the eigenvalue information onto the controller



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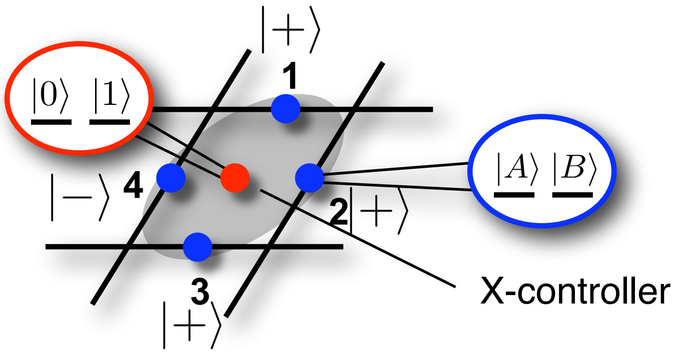
Hilbert space of the four spins



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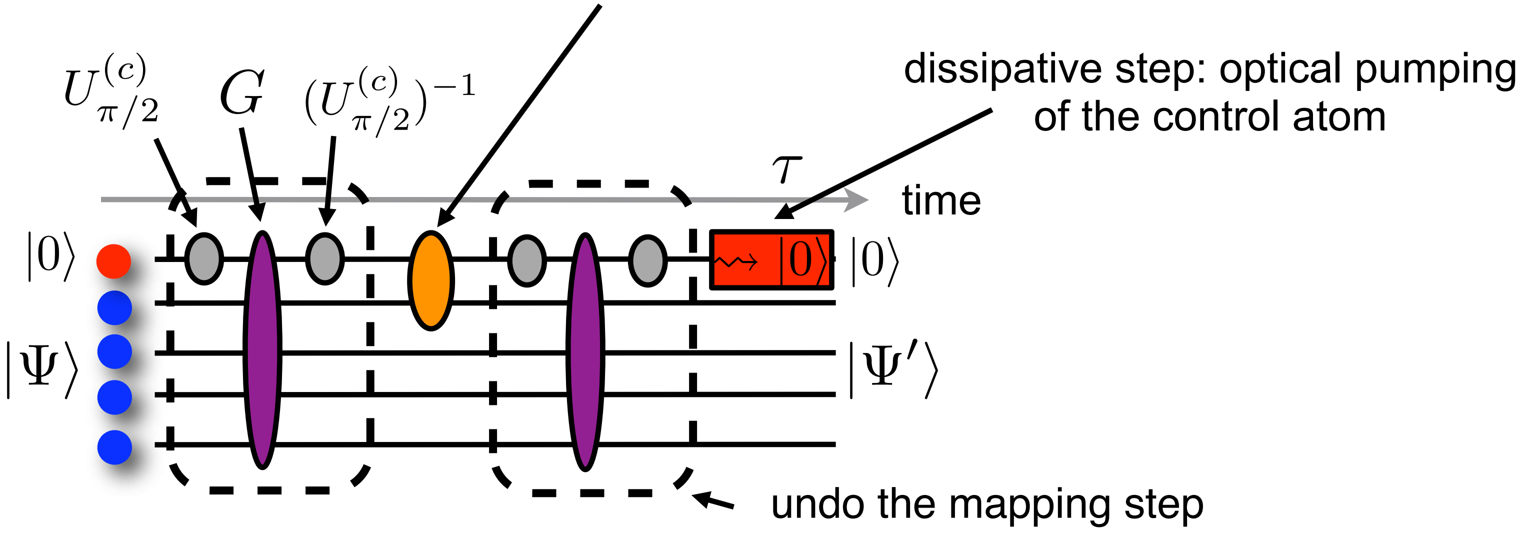
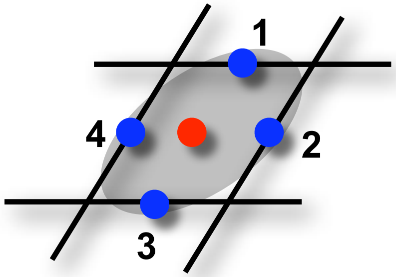


dissipative step: optical pumping of the control atom

undo the mapping step

Coherent and Dissipative Time Evolution



We have obtained ...

- Lindblad master equation

$$\frac{d}{dt}\rho = -i\,[H,\rho] + \gamma\left(c\rho c^\dagger - \frac{1}{2}c^\dagger c\rho - \rho\frac{1}{2}c^\dagger c\right)$$

- Coherent evolution: Hamiltonian

$$H = h\sigma_x^{(1)}\sigma_x^{(2)}\sigma_x^{(3)}\sigma_x^{(4)} \qquad (h = -\frac{\alpha}{\tau})$$

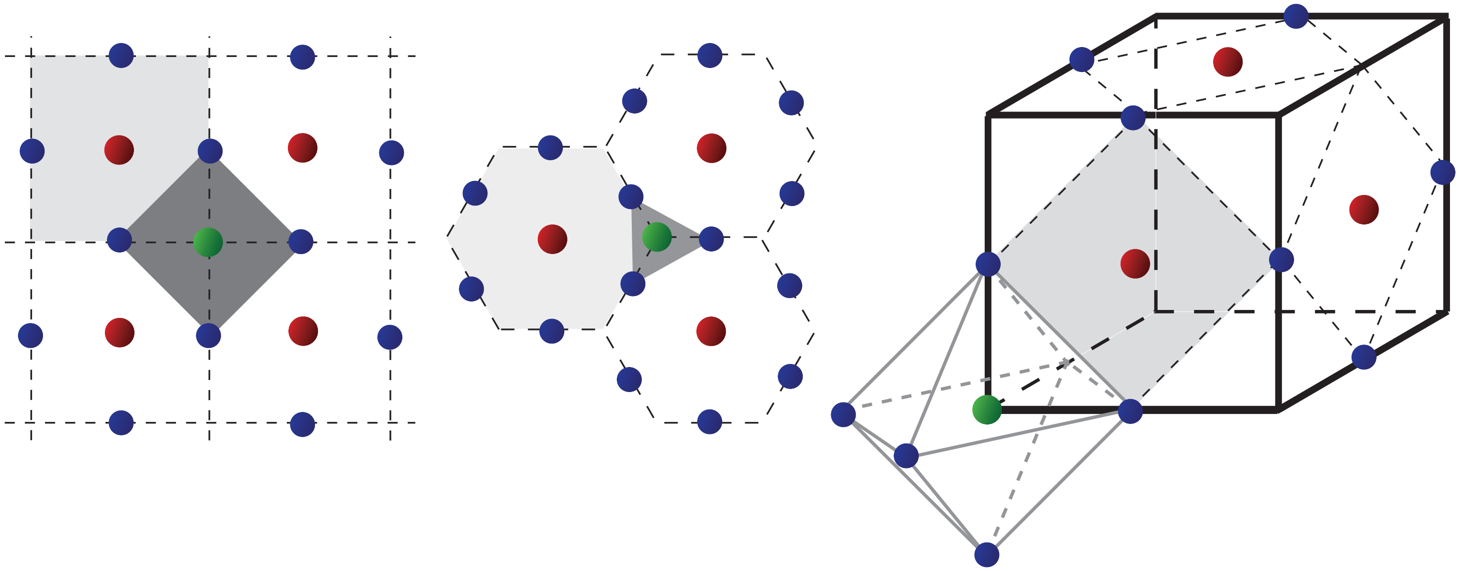
- Dissipative evolution: quantum jump operator

$$c = \sqrt{\gamma}\sigma_z^{(1)}\left(1 - \sigma_x^{(1)}\sigma_x^{(2)}\sigma_x^{(3)}\sigma_x^{(4)}\right) \qquad (\gamma = \frac{\phi^2}{\tau})$$

- Sweeping over the lattice ...
  - we simulate the toric code Hamiltonian
  - we pump into the ground state

Outlook

- **Rydberg quantum simulator**



Possible models: Kitaev toric code model, color codes, lattice gauge theories

Hybrid Quantum Systems

solid state

AMO

systems:

- superconducting qubits
- quantum dot spin qubits
- impurities: NV centers etc.
- nuclear spin ensembles
- photons / CQED
  - optical / photonic cavities
  - microwave / sc stripline
- nano-mechanics
  - opto-/electro-
- ...

- atoms, ions, molecules
  - single atoms and ensembles
  - trapping and cooling (BEC)
- photons / CQED
  - cavities: optical and microwave
  - free space
- ...

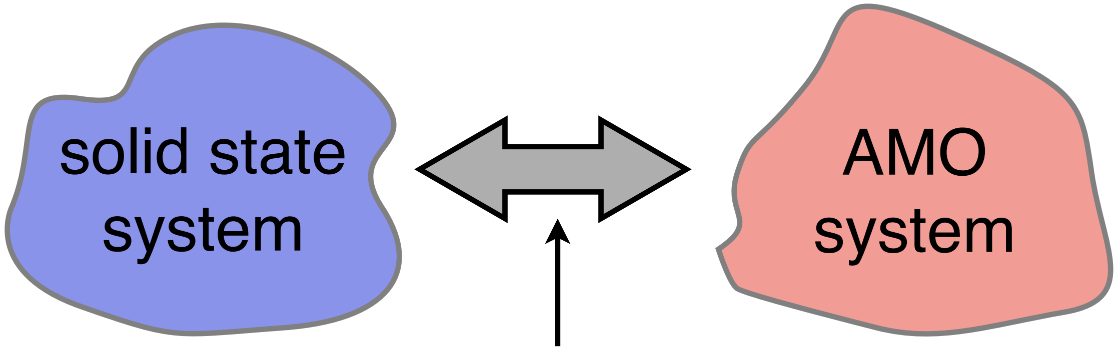
trademark:

- nanotechnology
- scalability

- “ideal” quantum systems

… success stories …

Hybrid Quantum Systems



solid state system

AMO system

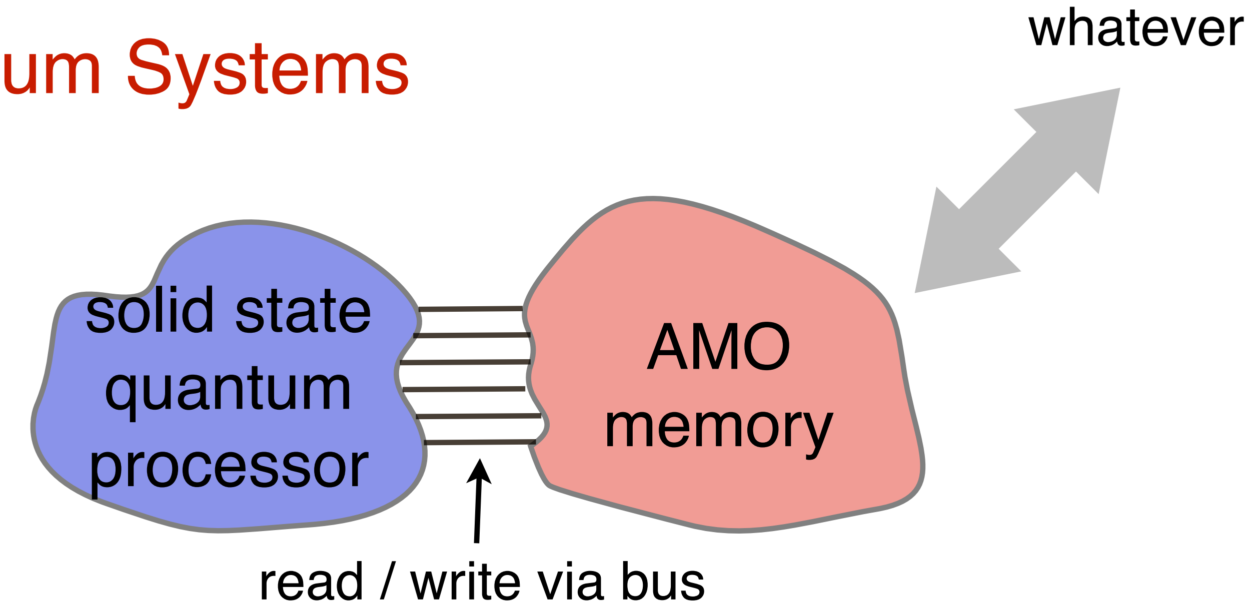
quantum interface
("quantum bus")

challenge: "hybrid systems"

- develop coherent quantum interface *between solid state and AMO systems*
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups

Hybrid Quantum Systems

example:



whatever

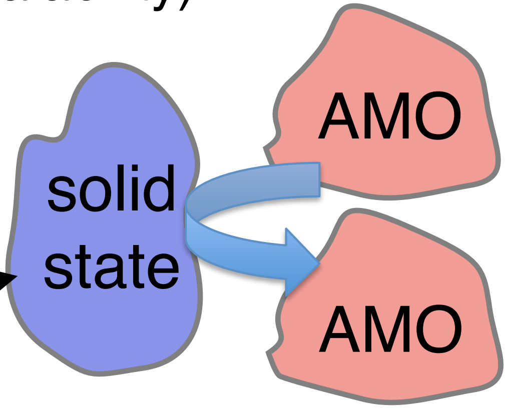
solid state quantum processor

AMO memory

read / write via bus

challenge: “hybrid systems”

- hybrid quantum processor
- ...
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...



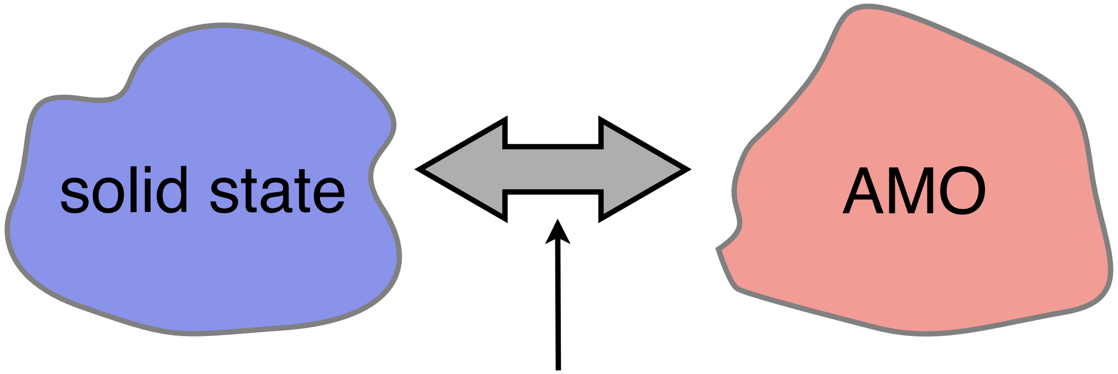
- nanotraps / scalable
- mediated interactions

solid state

AMO

AMO

Hybrid Quantum Systems



quantum interface
(“quantum bus”)

quantum interface - how?

- optical photons
- microwave photons

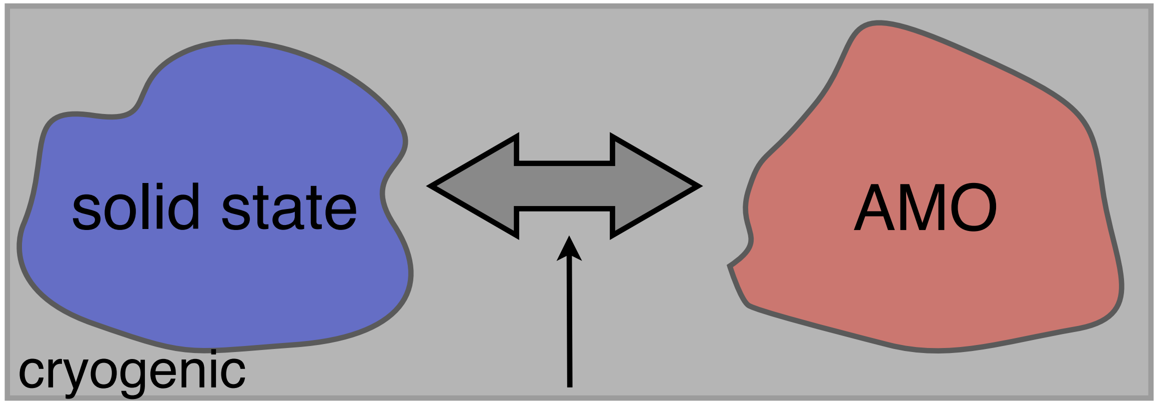
- direct coupling

- free space / long distance
- cavities

- trapping close to surface,
  in cryostat?

- deterministic &
  probabilistic protocols

Hybrid Quantum Systems



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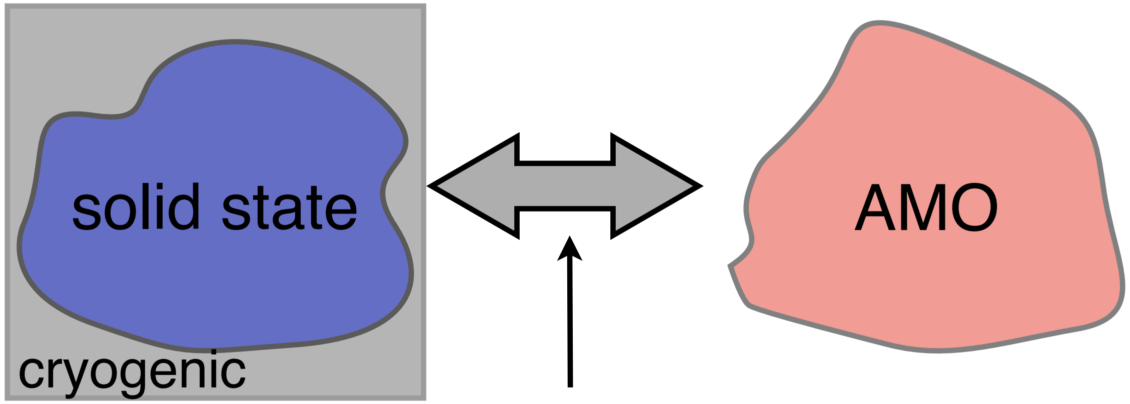
Hybrid Quantum Systems



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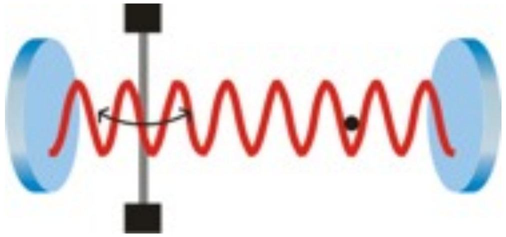
- deterministic & probabilistic protocols

Examples:

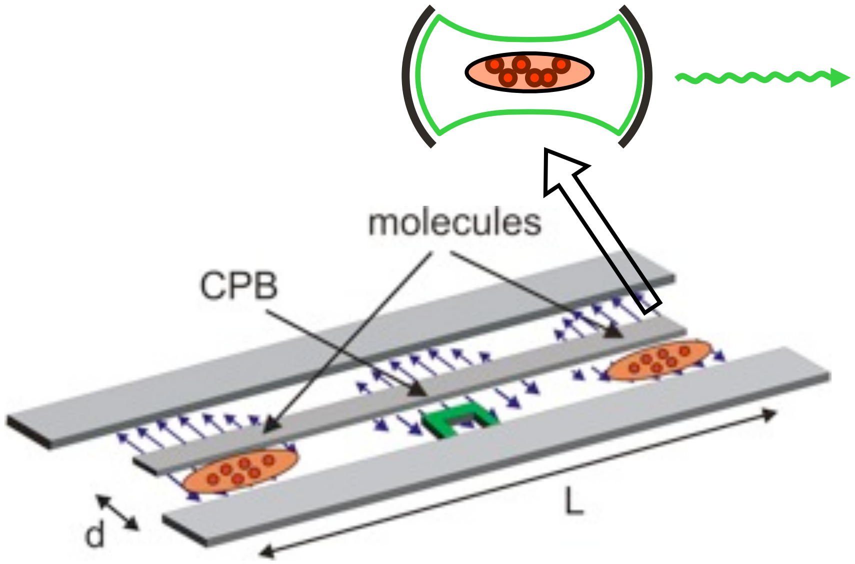
- **Opto-Nanomechanics + Atom(s)**
- Circuit QED + Polar Molecules
- CQED: Microtoroids + Atoms (Quantum Networks)
- Nanoscale AMO physics



membrane ⟷ single atom

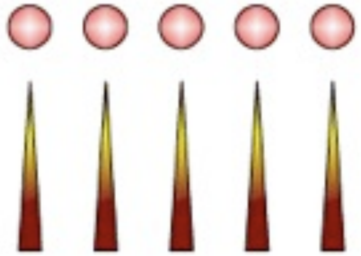
Caltech+Munich+Innsbruck

Hybrid Quantum Processors



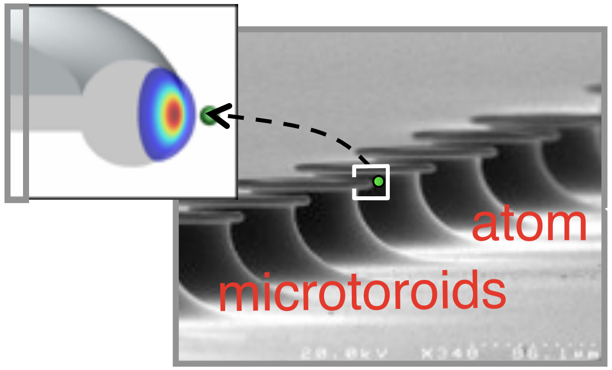
Harvard+Yale+Innsbruck

Nanoscale AMO



Caltech+Harvard+Yale+Innsbruck

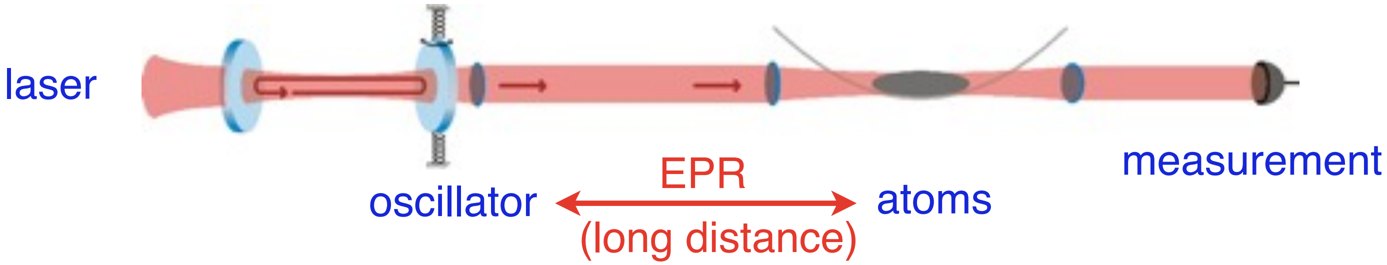
Quantum Networks



Caltech

Opto-nanomechanics + atom(s)

- **QND measurement based EPR entanglement between oscillator + atomic ensembles**



K. Hammerer,
M. Aspelmeyer,
E. Polzik,
P. Z.,
PRL 2009

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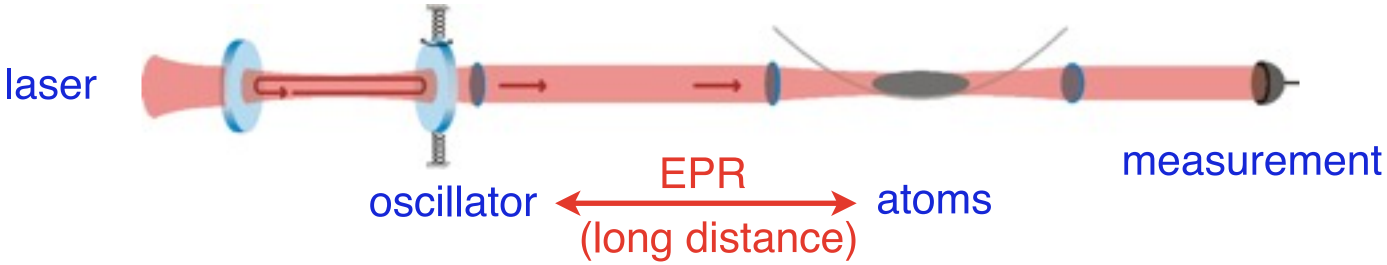

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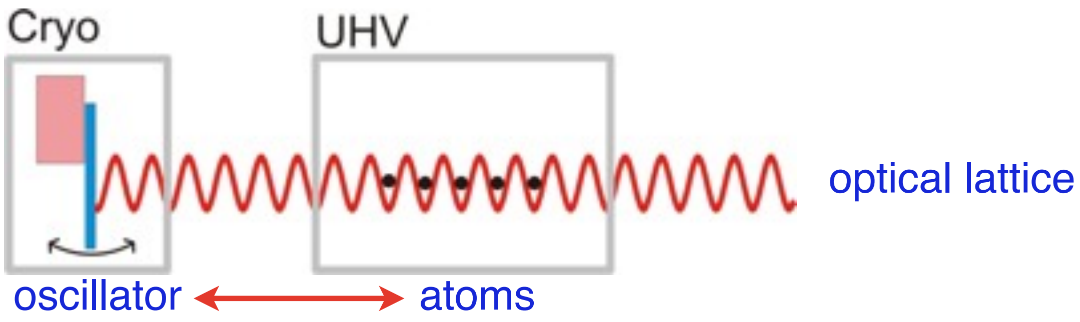
PRL 2009

- **Free space coupling between nanomechanical mirror + atomic ensemble**



Innsbruck
+
Munich

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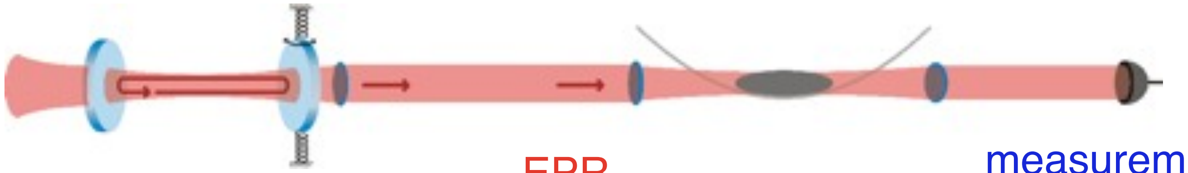


laser

oscillator ⟷ atoms

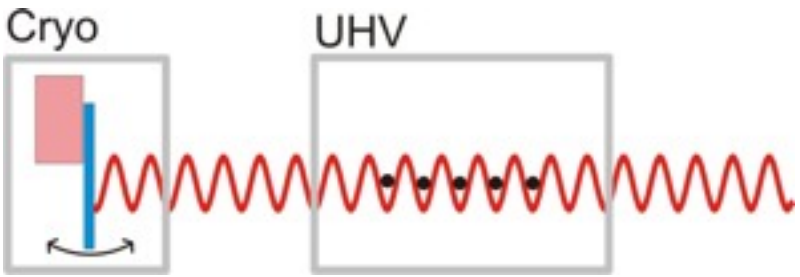
EPR

(long distance)

measurement

K. Hammerer,
M. Aspelmeyer,
E. Polzik,
P. Z.,
PRL 2009

- **Free space coupling between nanomechanical mirror + atomic ensemble**

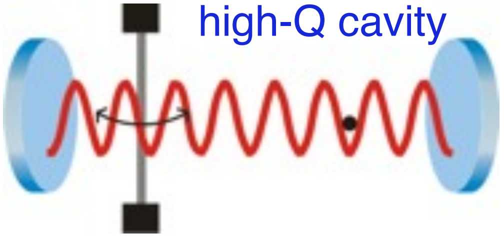


optical lattice

oscillator ⟷ atoms

Innsbruck
+
Munich

- **… and strong coupling between a *single* atom and a membrane**



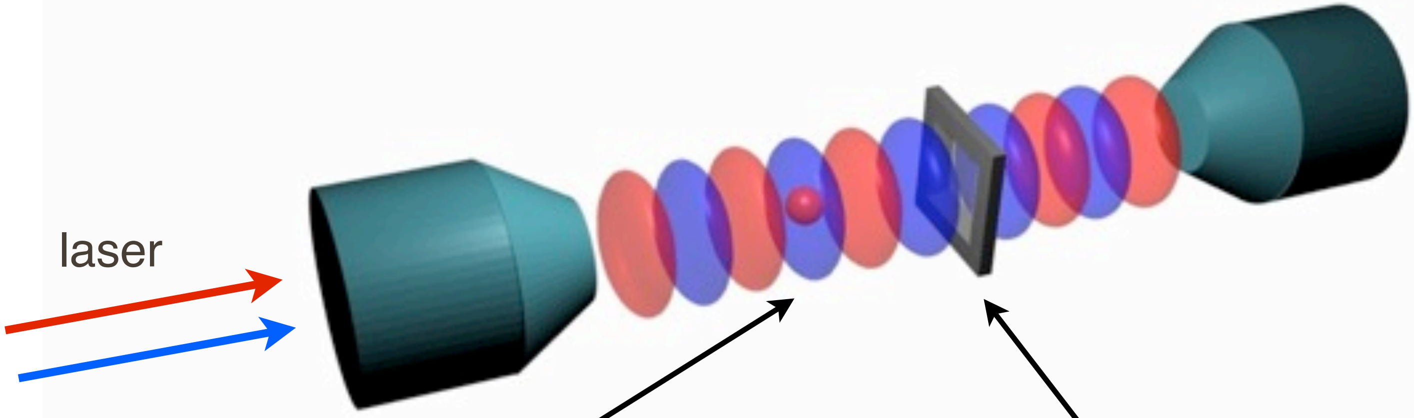
high-Q cavity

membrane ⟷ single atom

with existing experimental setups & parameters :-)

Caltech +
Munich +
Innsbruck,
preprint

Strong Coupling of Single Trapped Atom to Membrane



laser

atom trapped
in optical lattice

moving membrane

photons

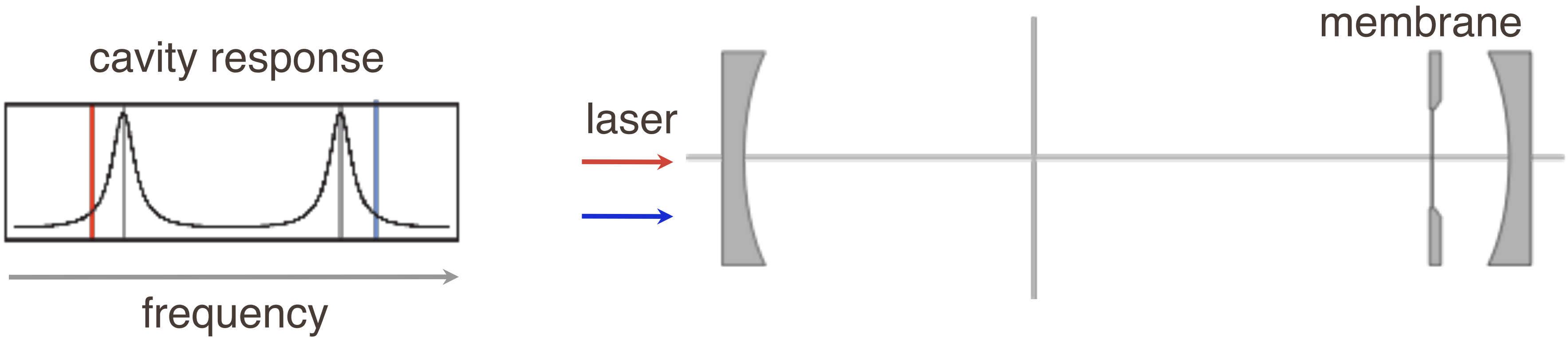
computer art:
F. Marquardt

✓cavity mediated: coupling ~ finesse

✓ coherent coupling >> dissipation

K. Hammerer, C. Genes, M. Wallquist, P. Treutlein, M. Ludwig, F. Marquardt, J. Ye, J. Kimble, PZ

Strong Coupling of Single Trapped Atom to Membrane



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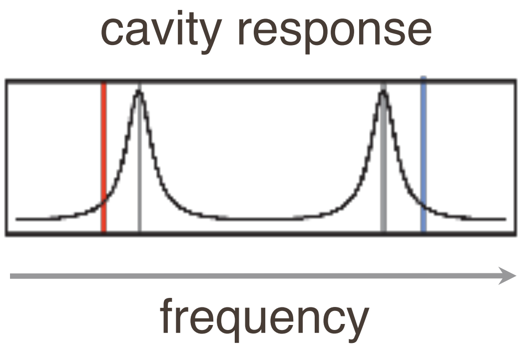

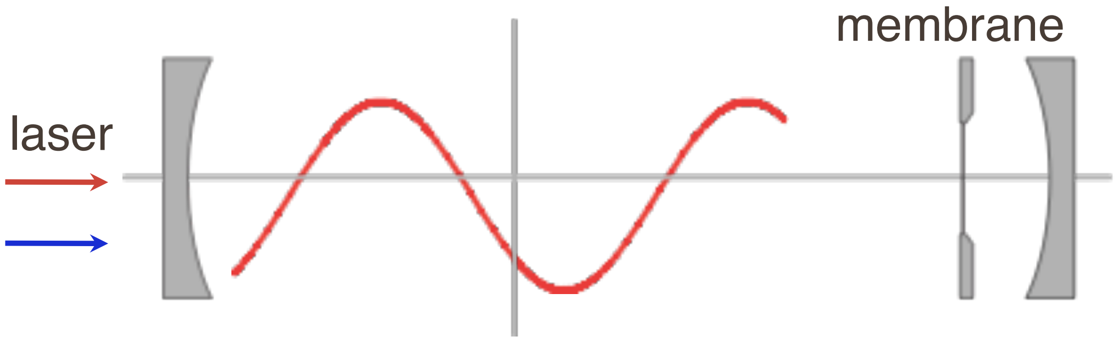

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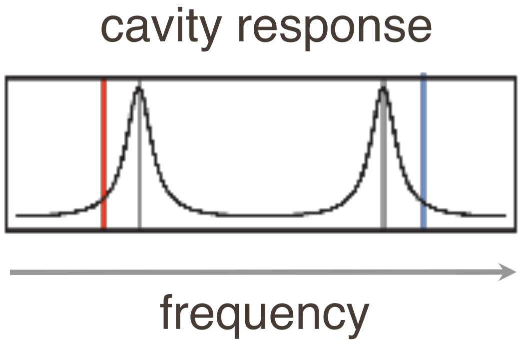

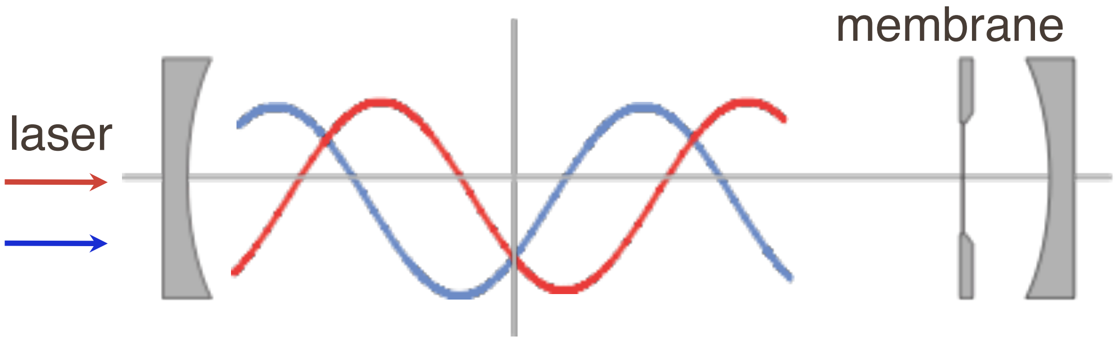

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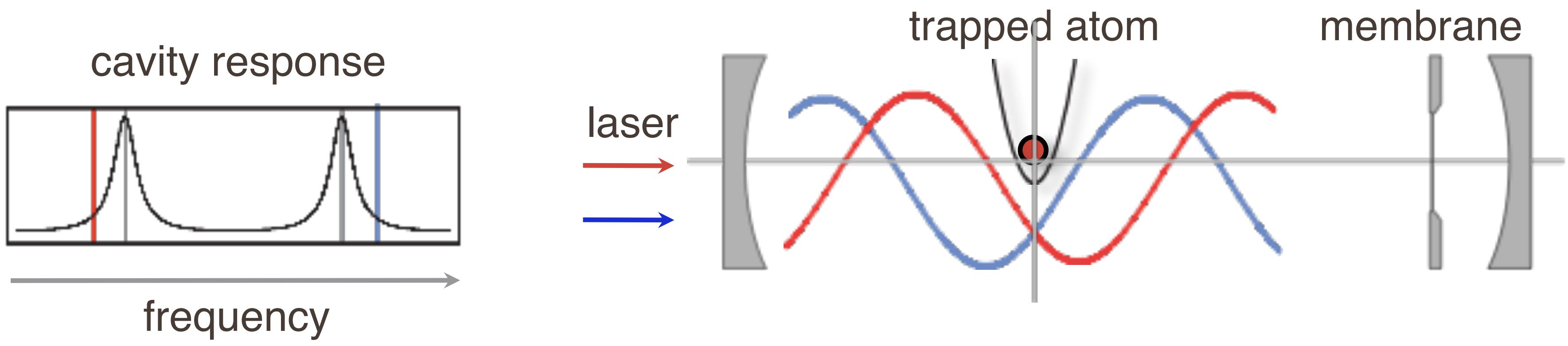

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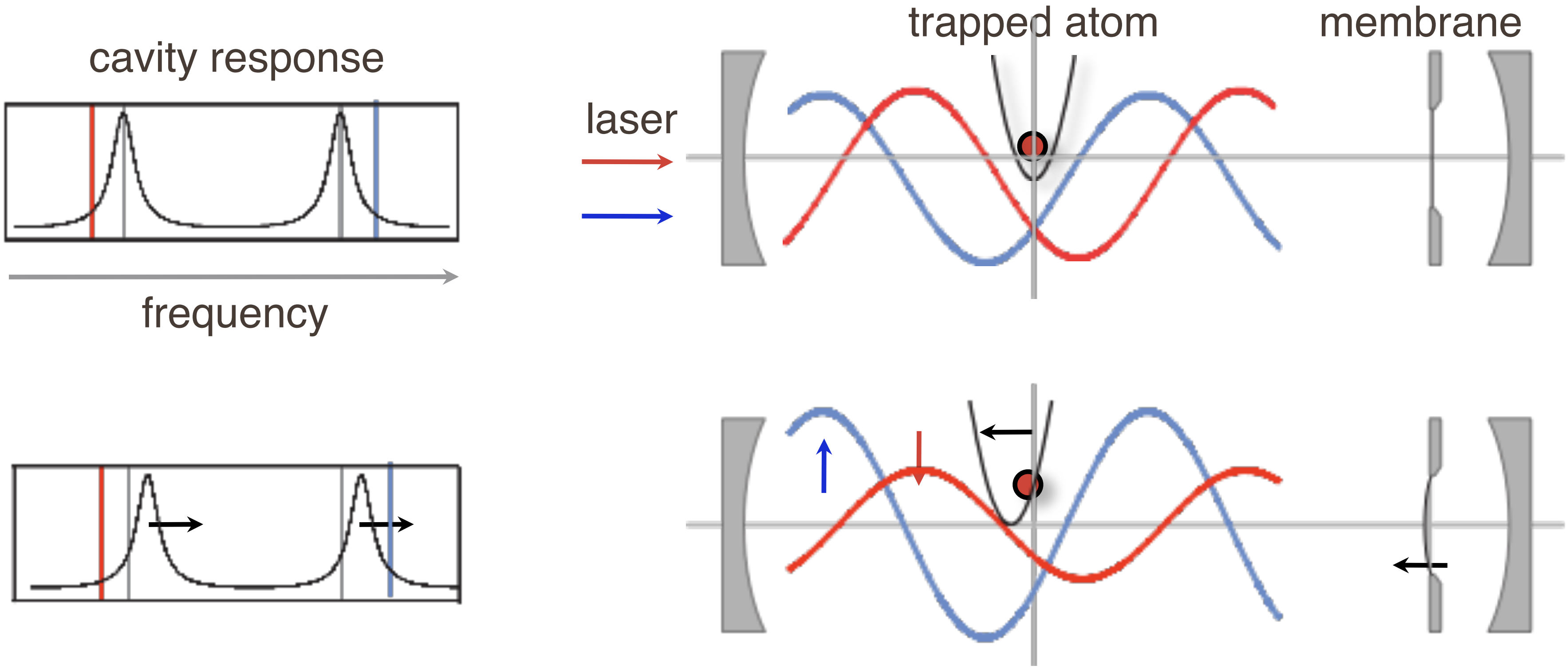


cavity response

frequency

laser

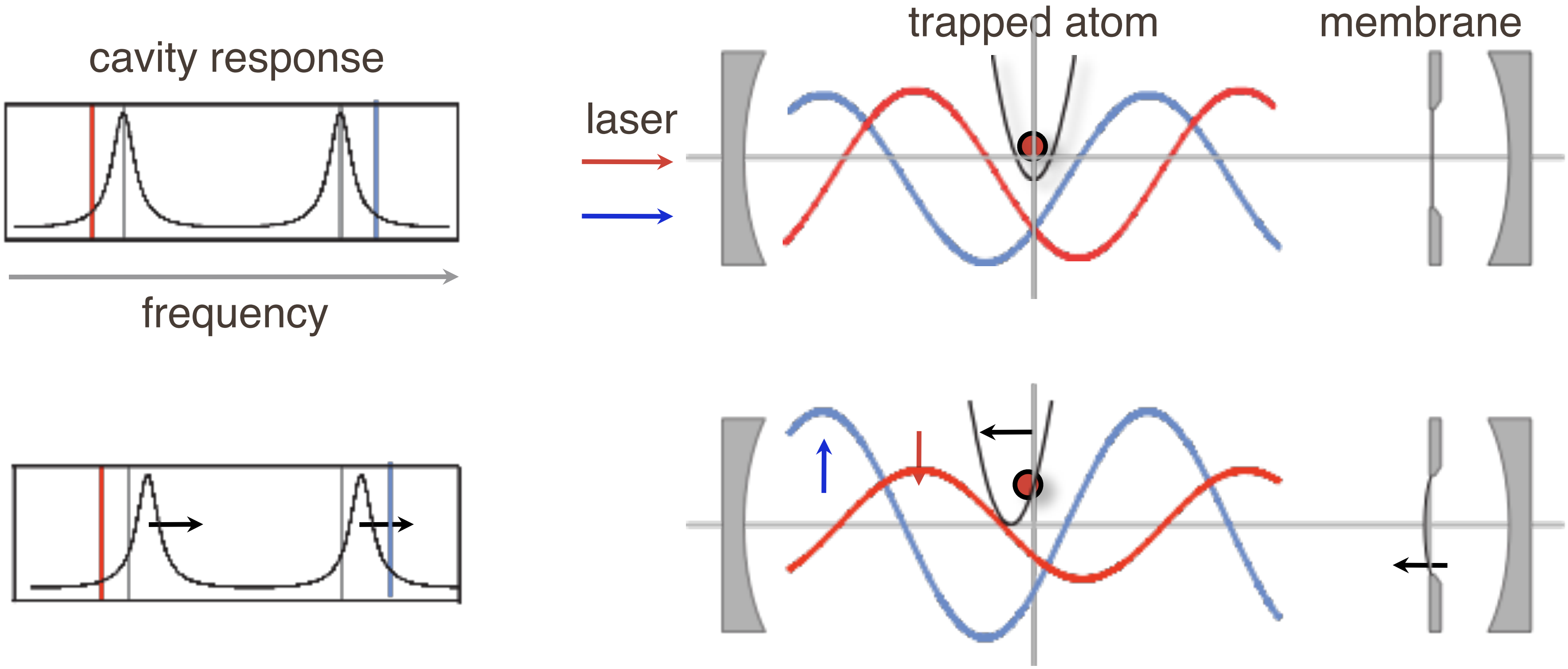
trapped atom

membrane

moving membrane displaces atom trap

coupling ~ finesse

Strong Coupling of Single Trapped Atom to Membrane



moving membrane displaces atom trap

coupling ~ finesse

- coherent coupling >> dissipation

$$H = \omega_{\mathrm{m}} a_m^\dagger a_m + \omega_{\mathrm{t}} a_a^\dagger a_a + g(a_m^\dagger a_a + \mathrm{h.c.})$$

oscillator atom

- (quantum) noise & imperfections

membrane:
✓damping
✓temperature
✓laser heating

atom + cavity:
✓cavity damping
✓spontaneous emission
✓...

Numbers: strong coupling for existing setups & parameters

ADJUSTABLE PARAMETERS

mechanical frequency: $\omega_m / 2\pi$ = 0.78 MHz

membrane mass: m_m = 1.00 ng

cavity length: L = 50. μm

cavity waist: w0 = 10.00 μm

detuning from cavity resonance: Δ = 9.99 × κc

imbalance in couplings: s = 0.65 = $\frac{g0}{G0}$

rotating wave parameter: r = 0.100 = $\frac{\lambda}{\omega_m}$

FIGURES OF MERIT

Lamb Dicke parameter: kc×lat = 0.051

decoherence due to cavity decay: $\frac{\Gamma c}{\lambda}$ = 0.055

decoherence due to spontaneous emission: $\frac{\Gamma at}{\lambda}$ = 0.056

decoherence due to thermal heating: $\frac{\Gamma m}{\lambda}$ = 0.053

circulating power: P_{circ} = 3.94 mW

sideband parameter: $\frac{\kappa c}{\omega m}$ = 19.00

relative shift of lattices: l = 1.60 nm

ABSOLUTE NUMBERS

Atom-membrane coupling: $\lambda / 2\pi$ = 78.00 kHz

Decoherence rate due to cavity decay: $\Gamma c / 2\pi$ = 4.33 kHz

Decoherence rate due to spontaneous emission: $\Gamma at / 2\pi$ = 4.36 kHz

Decoherence rate due to thermal heating: $\Gamma m / 2\pi$ = 4.17 kHz

detuning from atomic resonance: $\delta / 2\pi$ = 9.81 GHz

single photon Rabi frequency: gc$/ 2\pi$ = 73.7 MHz'

energy shift per single photon and single atom: U$/ 2\pi$ = 553. kHz

single photon optomechanical coupling: g0$/ 2\pi$ = 18.5 kHz

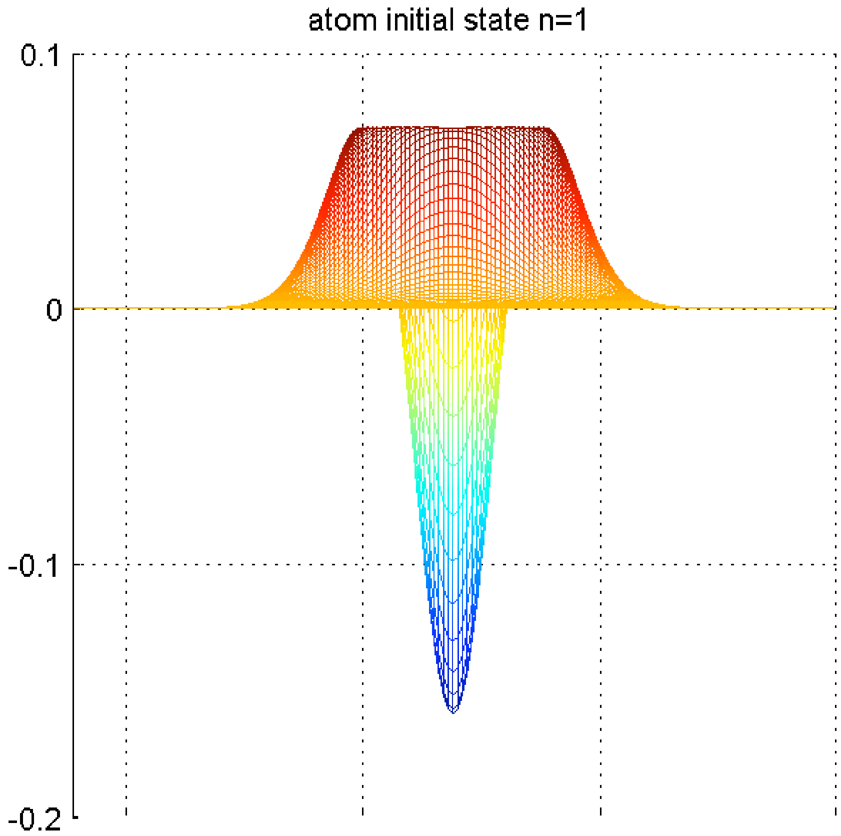
K. Hammerer, C. Genes

H. J. Kimble & J. Ye

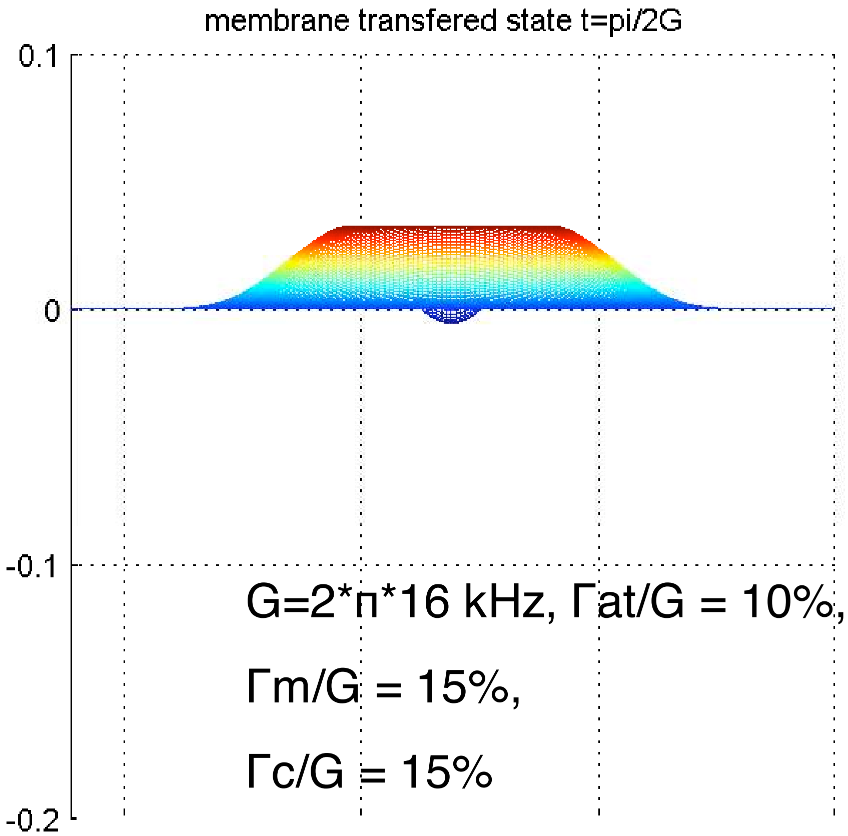
P. Treutlein

Transfer of a n=1 Fock state: membrane - atom

Wigner function atom



Wigner function membrane



G=2*π*16 kHz, Γat/G = 10%,

Γm/G = 15%,

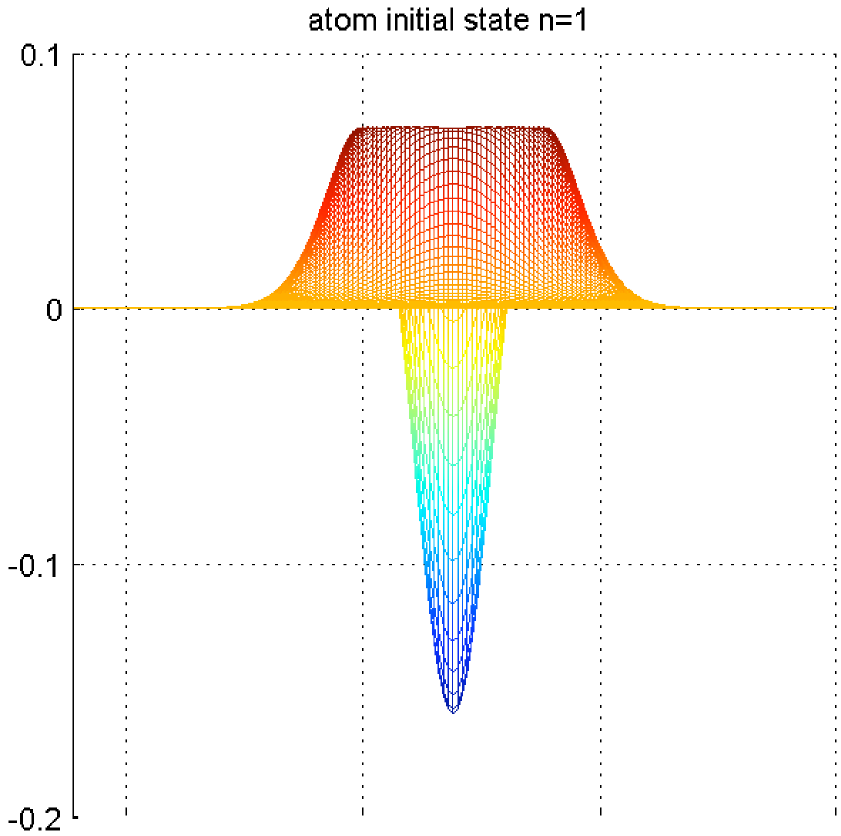
Γc/G = 15%

bad / good ~ 15%

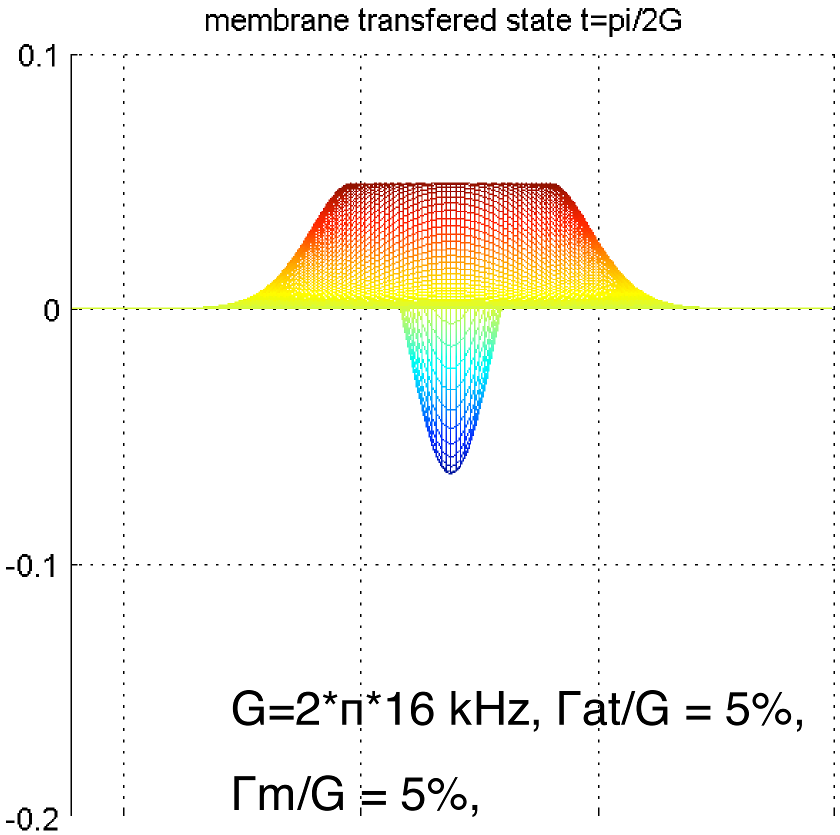
(present experimental parameters)

Transfer of a n=1 Fock state: membrane - atom

Wigner function atom



Wigner function membrane



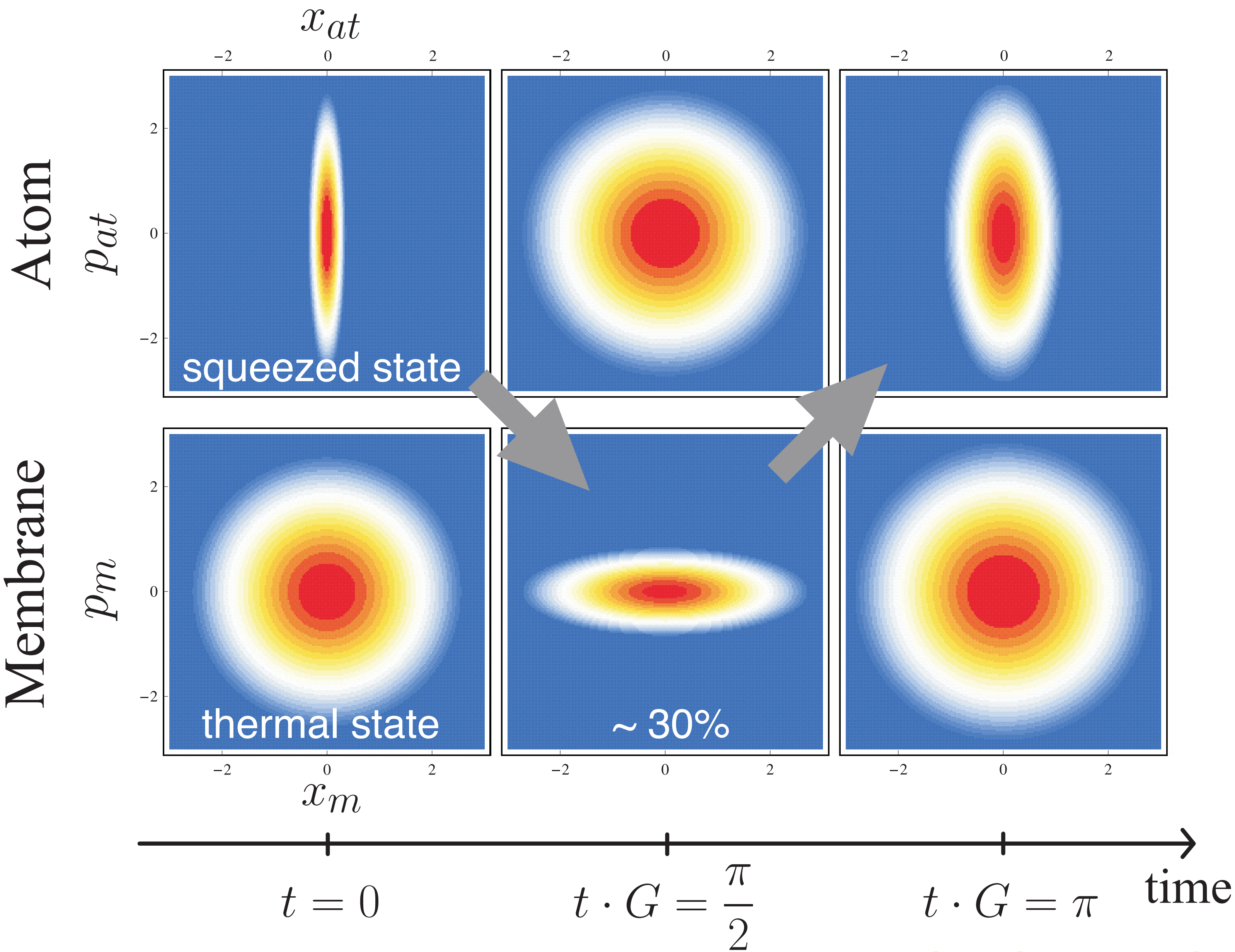
G=2*π*16 kHz, Γat/G = 5%,

Γm/G = 5%,

Γc/G = 5%

bad / good ~ 5%

Transfer of a Squeezed State

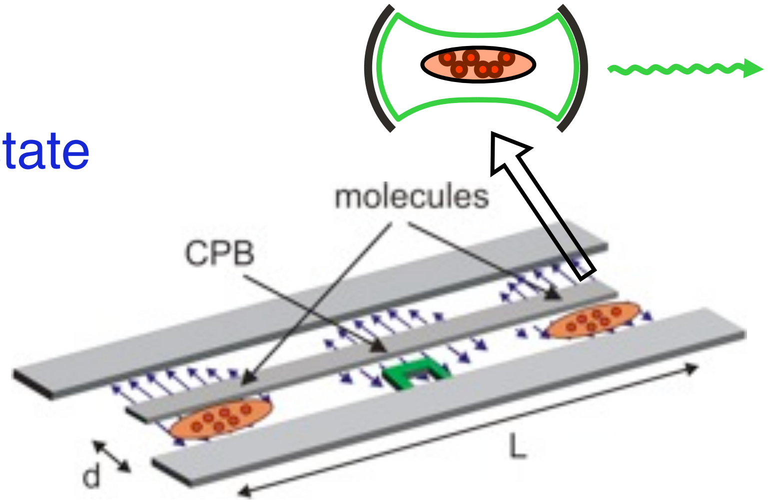


bad / good ~ 10%

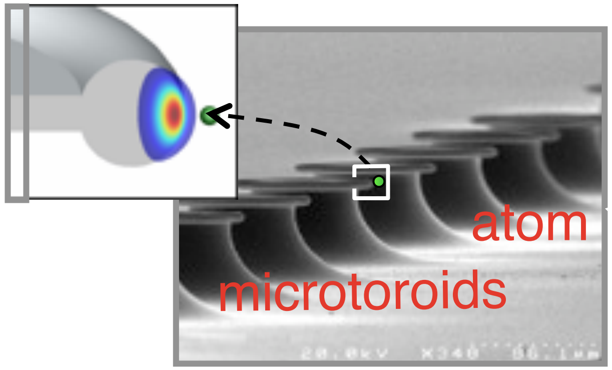
Conclusions and Outlook

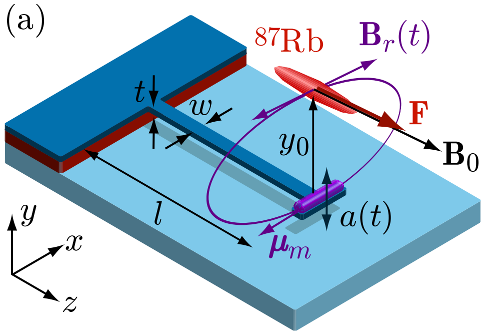
- develop coherent quantum interface between solid state and AMO systems
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups
- hybrid quantum processor
- AMO based preparation / measurement / sensors
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...

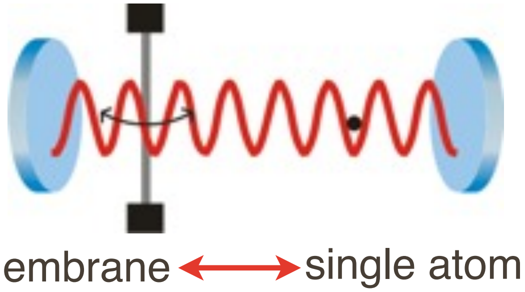
Hybrid Quantum Processors



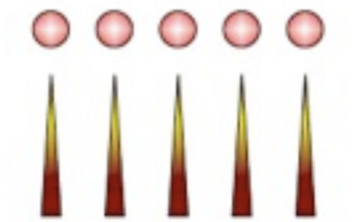
Quantum Networks







Nanoscale AMO

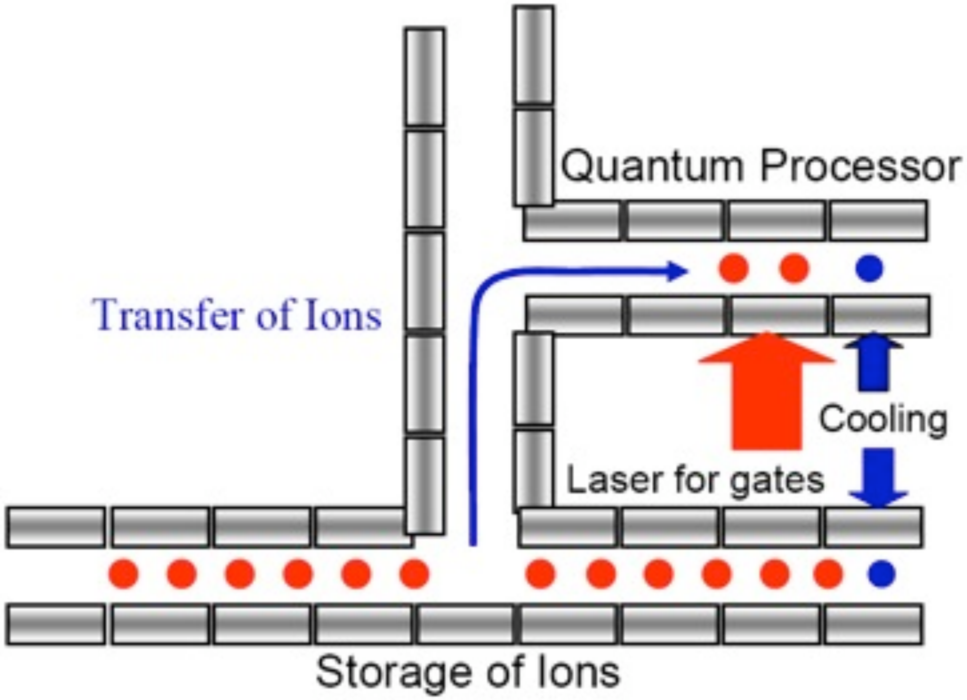


Traps for AMO:
… integration of AMO with on-chip devices
… towards AMO physics on the nanoscale

Scalable Ion Trap Quantum Computing

- **present approach:** physically transporting qubit

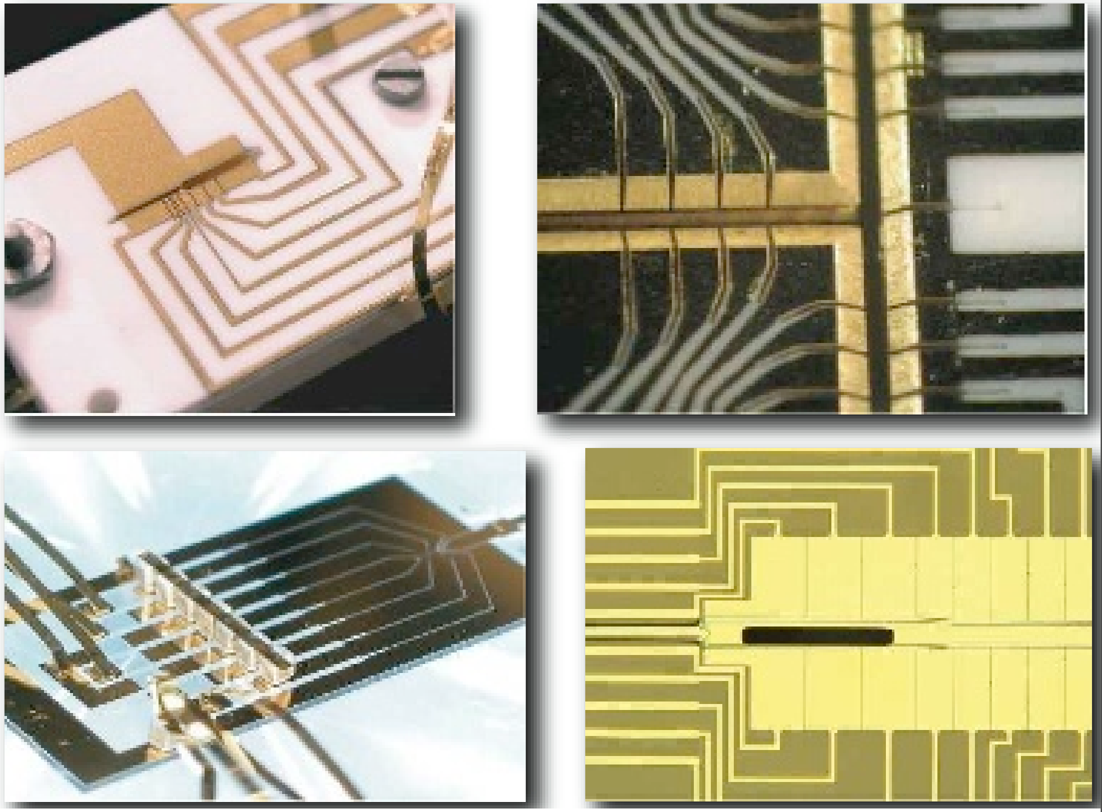
ion trap quantum computer



idea: Wineland et al.

exp.: Innsbruck, NIST Boulder, JQI, Oxford,...

cryogenic traps: MIT



R. Slusher, Georgia Tech

(also: C. Monroe & K. Schwab)

50 μm scale

Scalable Ion Trap Quantum Computing

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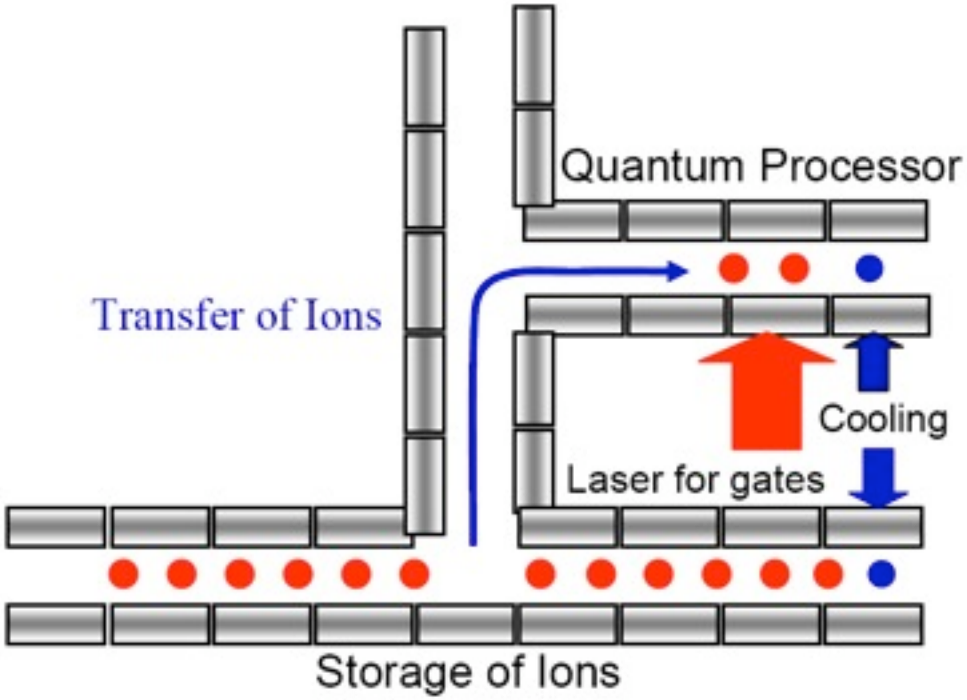

idea: Wineland et al.

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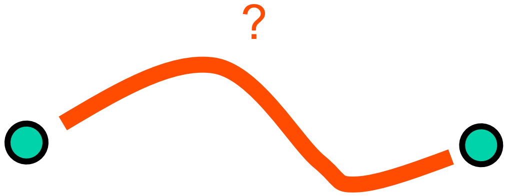
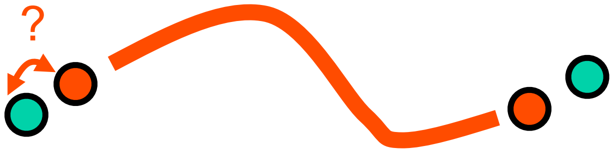
cryogenic traps: MIT

- **hybrid**

e.g. wire



connecting two quantum optical qubits by a (passive) solid state bus



interfacing active devices

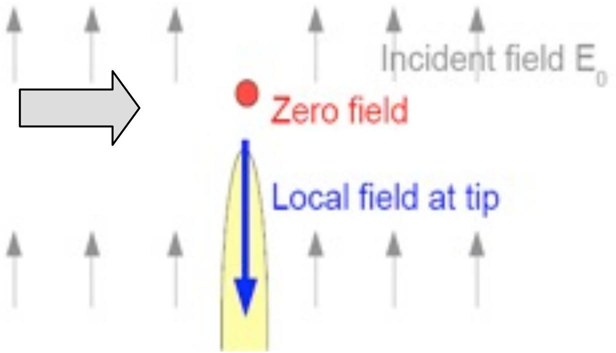
theory: L. Tian et al.

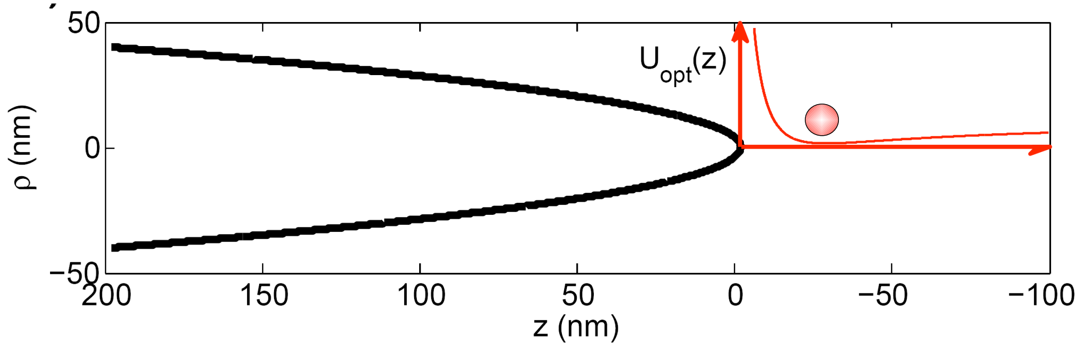
exp.: H. Häffner & R. Blatt / Walraff

compare: polar molecule / Rydberg

Towards AMO physics on the nanoscale

- Tightly confined radiation for trapping, cooling of isolated atoms
- Example: dipole traps & optical lattices using plasmons





1. sharp, conducting nanotip illuminated by light: "lightning rod" effect = trap

2. coupling to plasmon modes = read out, (and interactions)

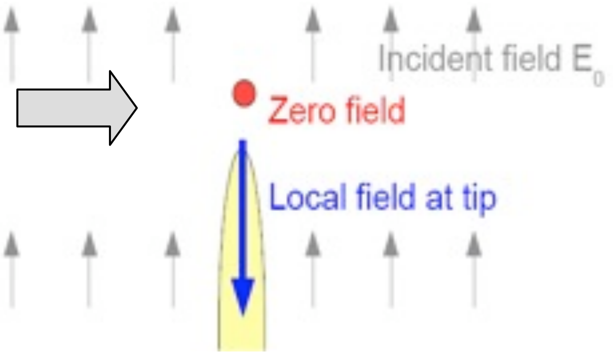
3. surface effects: Van der Waals and "polarization noise"

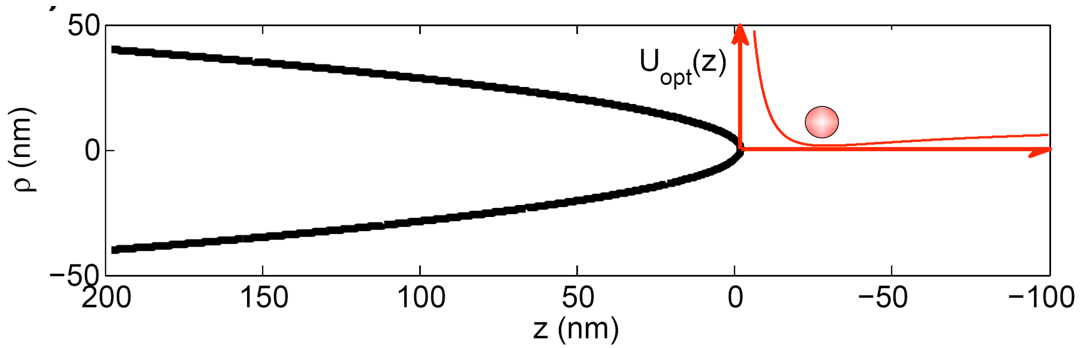
- Tight atom confinement, large energy scales
- Strong blue "shield" for nanotip:
  for suspended wires van der Waals significant only @ distances < wire size

D.Chang et al., Park / PZ / M Lukin, in preparation
See also: nano-particle plasmon tweezer @ICFO (Barcelona), atoms around nanotubes ideas (Hau)

Towards AMO physics on the nanoscale

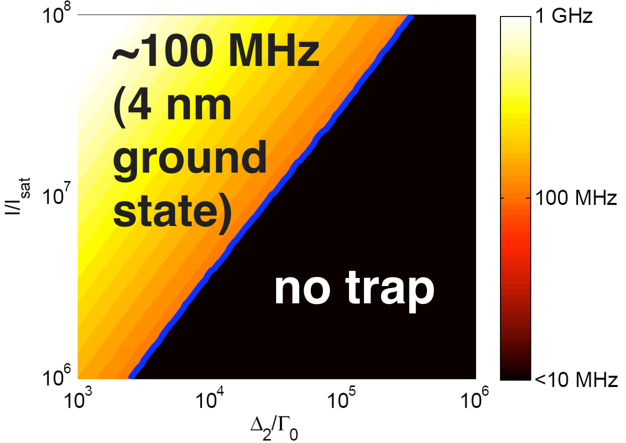
- Tightly confined radiation for trapping, cooling of isolated atoms
- Example: dipole traps & optical lattices using plasmons



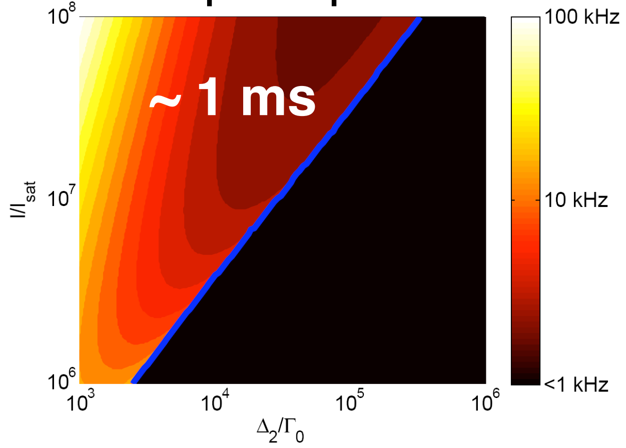


- silver nanotip and sodium atoms
  - Distance from trap $z_{\text{trap}} = 30$nm
  - Effective cooperativity $C \sim 4$

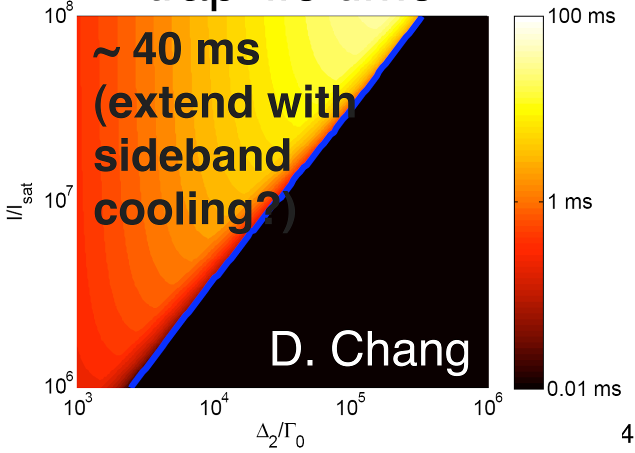
trap frequency



spin flip rate

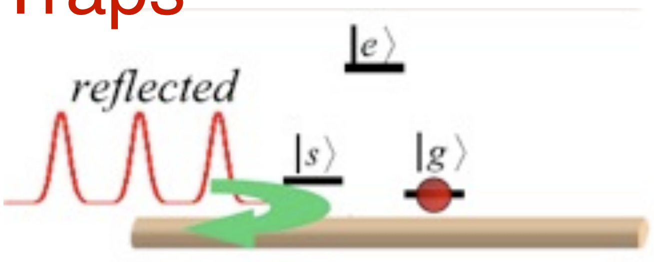


trap life time



Potential Applications of Nanoscale Traps

- Nonlinear optics:
  single photon switches and transistors



D. Chang et al, Nature Physics (2007)

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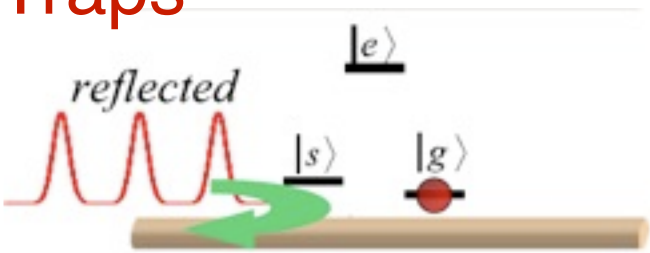

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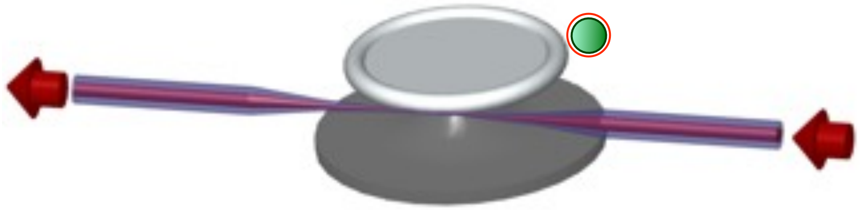

- Single atom positioning
  and control for CQED

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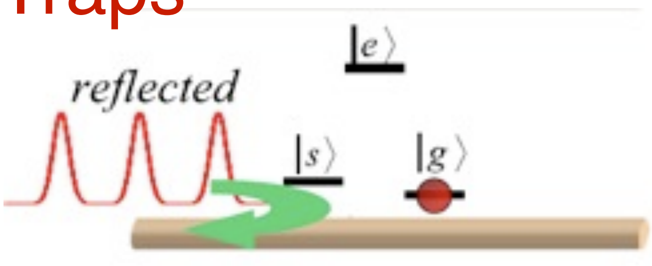

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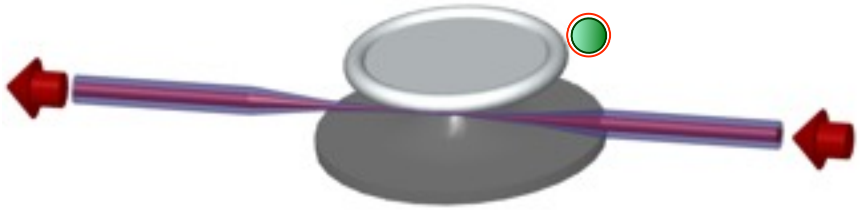

- Single atom positioning
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- Scanning sensors based on
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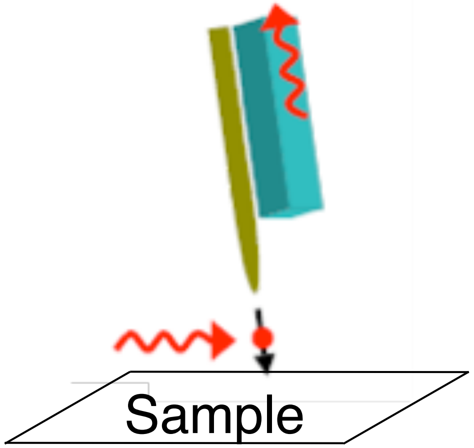

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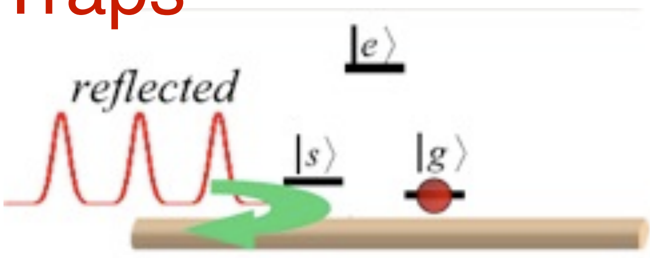

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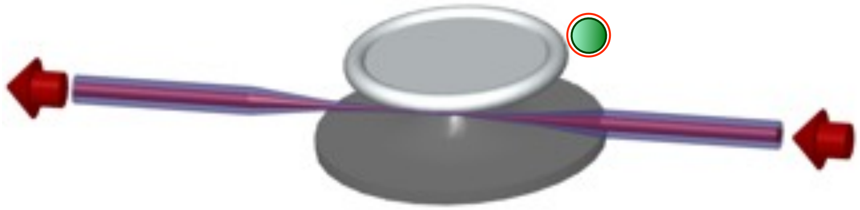

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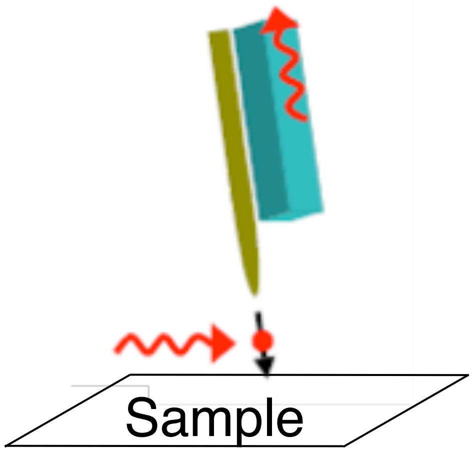

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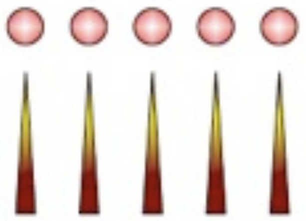

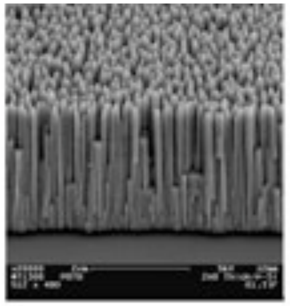

- Lattices with sub-wavelength
  control
  (e.g quantum simulation)