Developing theoretical and experimental tools for a hybrid quantum simulation using trapped ions

Sainath Motlakunta

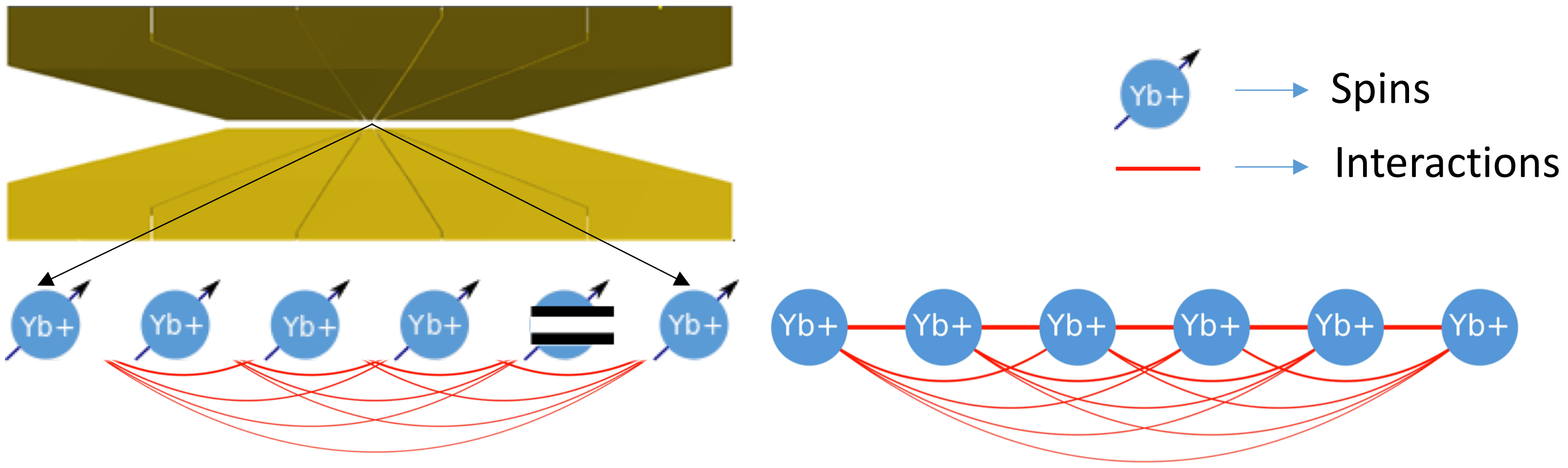
Quantum Information with Trapped Ions (QITI) Group

Talk outline

- **Part1: Theoretical tools:** A scheme to engineer programmable spin interaction graphs in a trapped ion quantum simulator.

- **Part2: Experimental tools:** Laser frequency stabilization for ion trap experiments

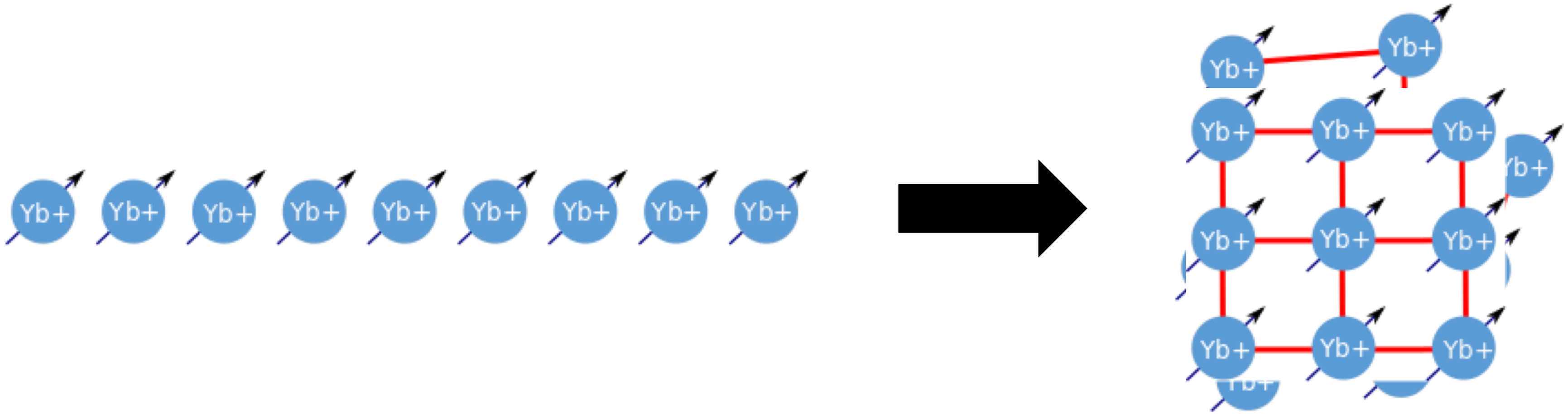
Trapped ions as Quantum Simulator



- Long coherence times (>10 min single qubit coherence time*)
- Ease of state preparation and isolation
- Controlled long range interactions
- Flexible fully connected graphs
- Useful to simulate systems with larger number of long range interactions

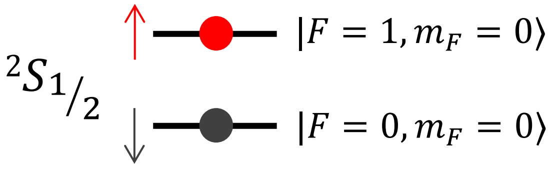
*Ye Wang et al *Nature Photonics* **11**, 646–650 (2017)

Engineer programmable spin interaction graphs

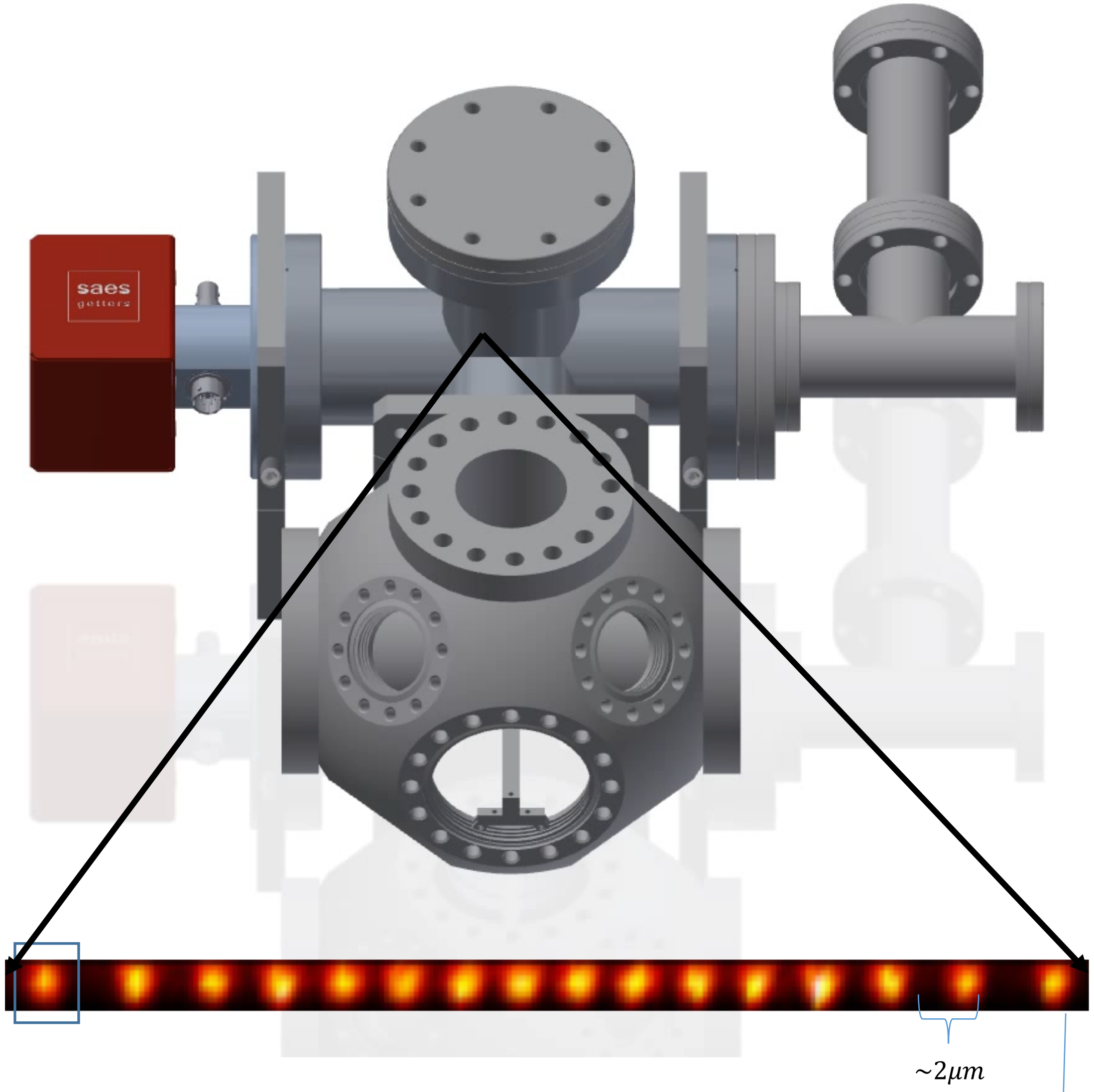


we propose a quantum simulation protocol to engineer XY spin dynamics on a 2D lattice with 1D chain of ions.

$^{171}Yb^{+}$ Ion Quantum Simulator

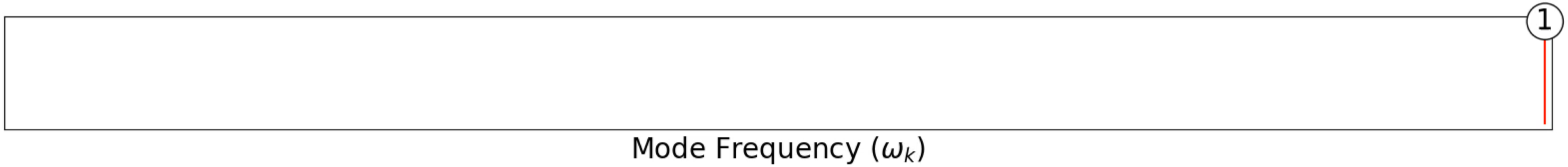


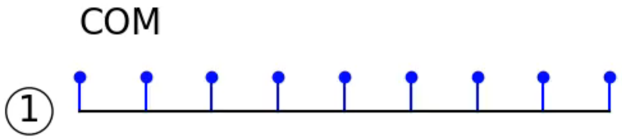
$^{171}Yb^{+}$Qubit



CCD image of ions
University of Maryland/JQI
ion group

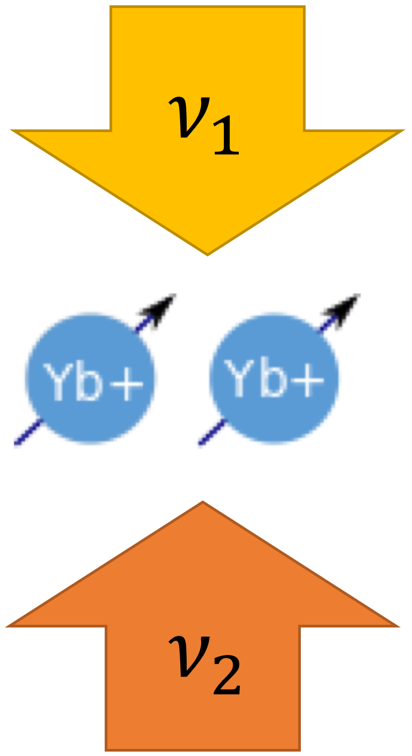
Normal modes of a chain of ions



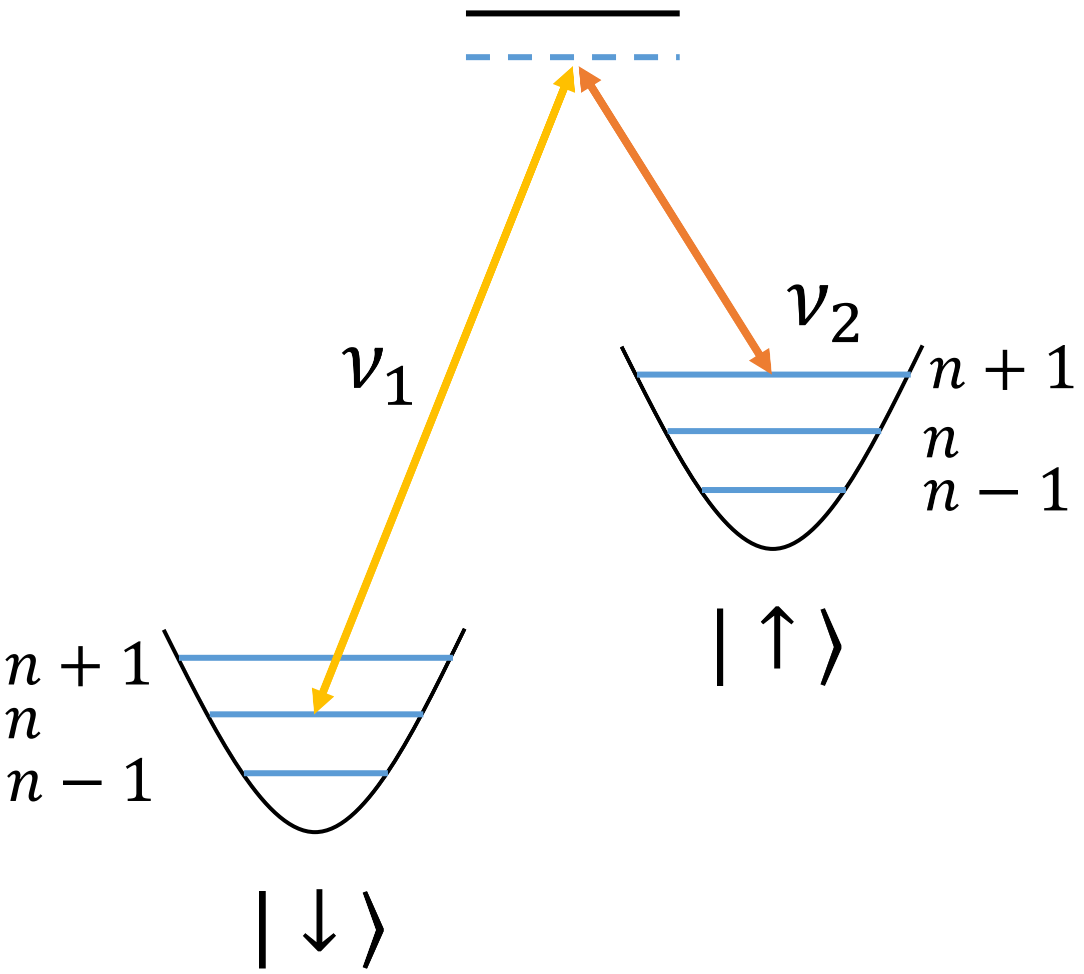


$\} \; b_i^k$

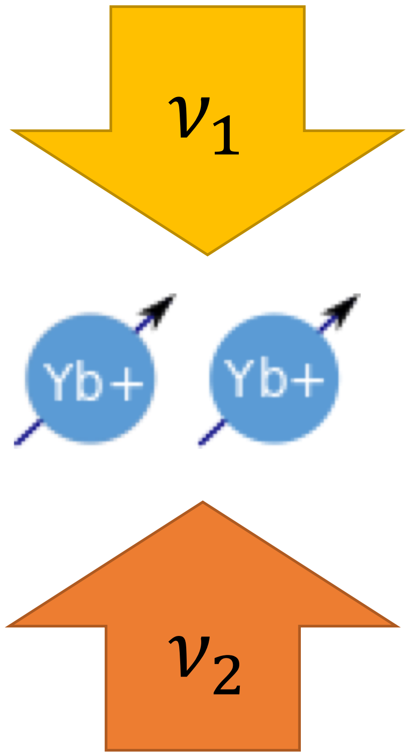
Phonon mediated spin-spin interactions

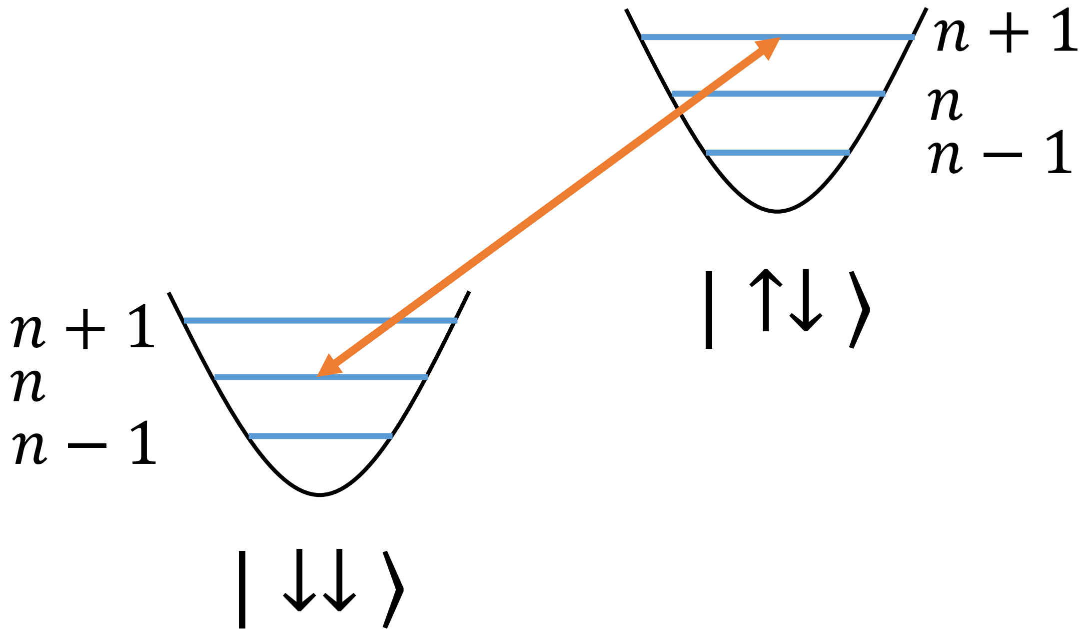


Global laser beams

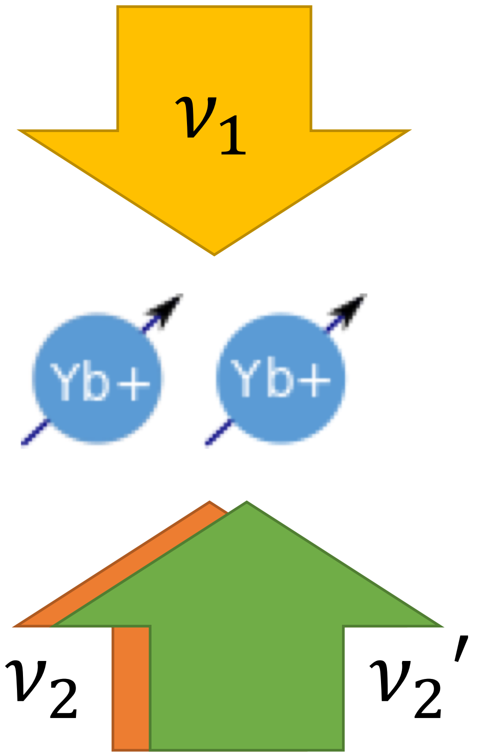


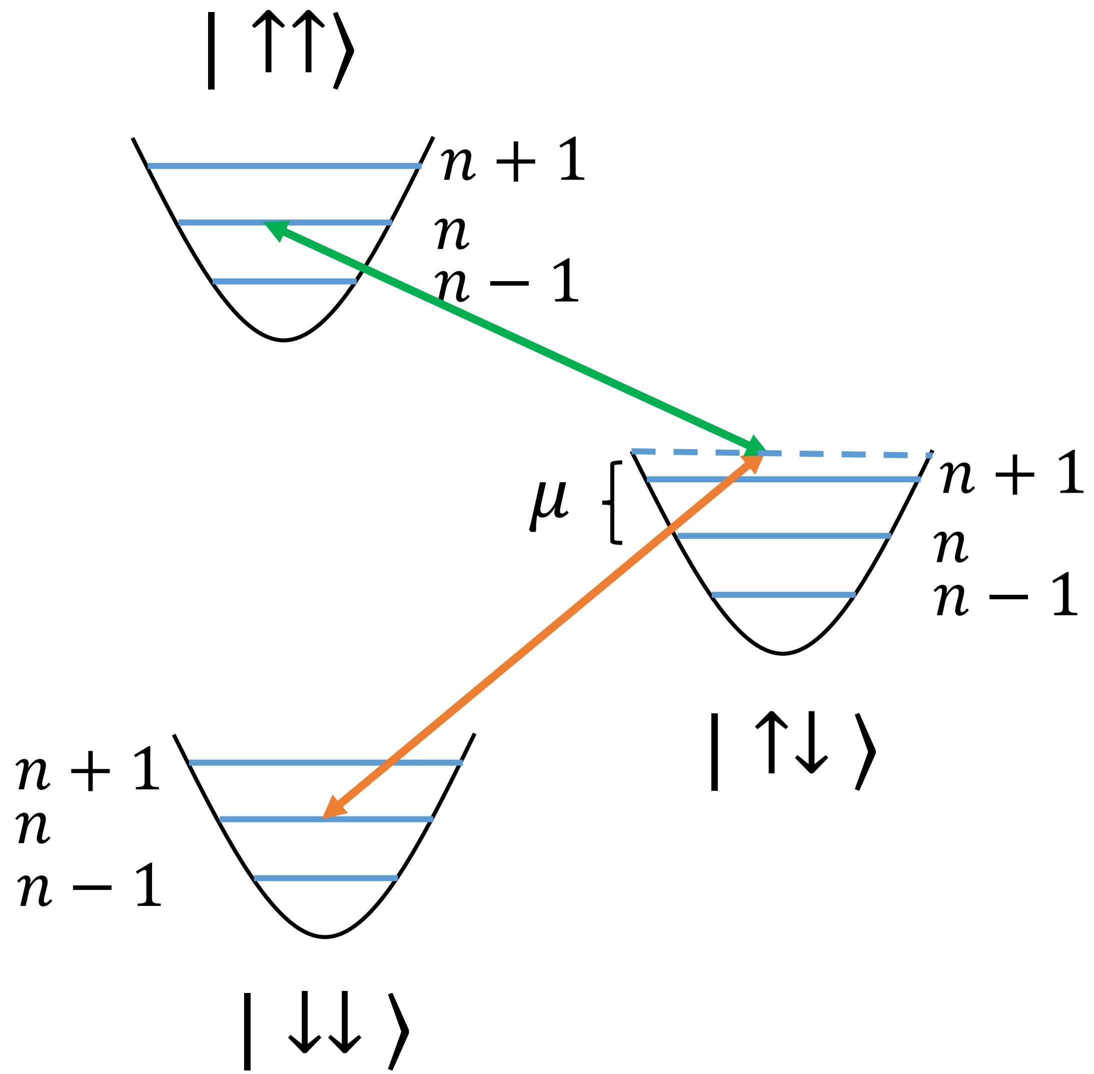
Phonon mediated spin-spin interactions



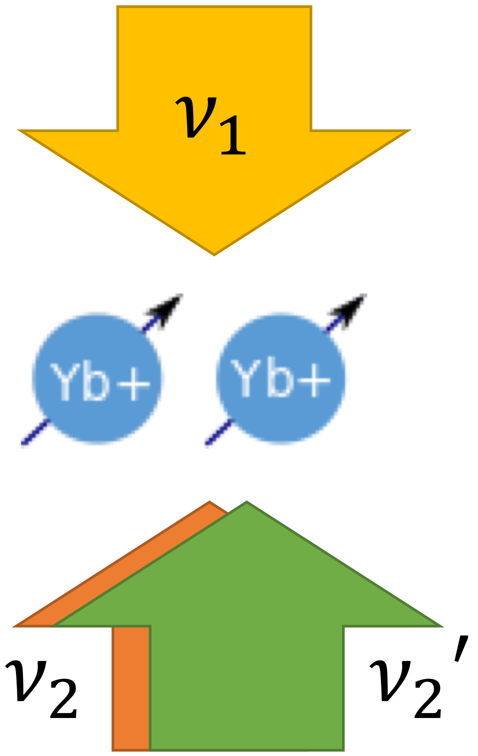


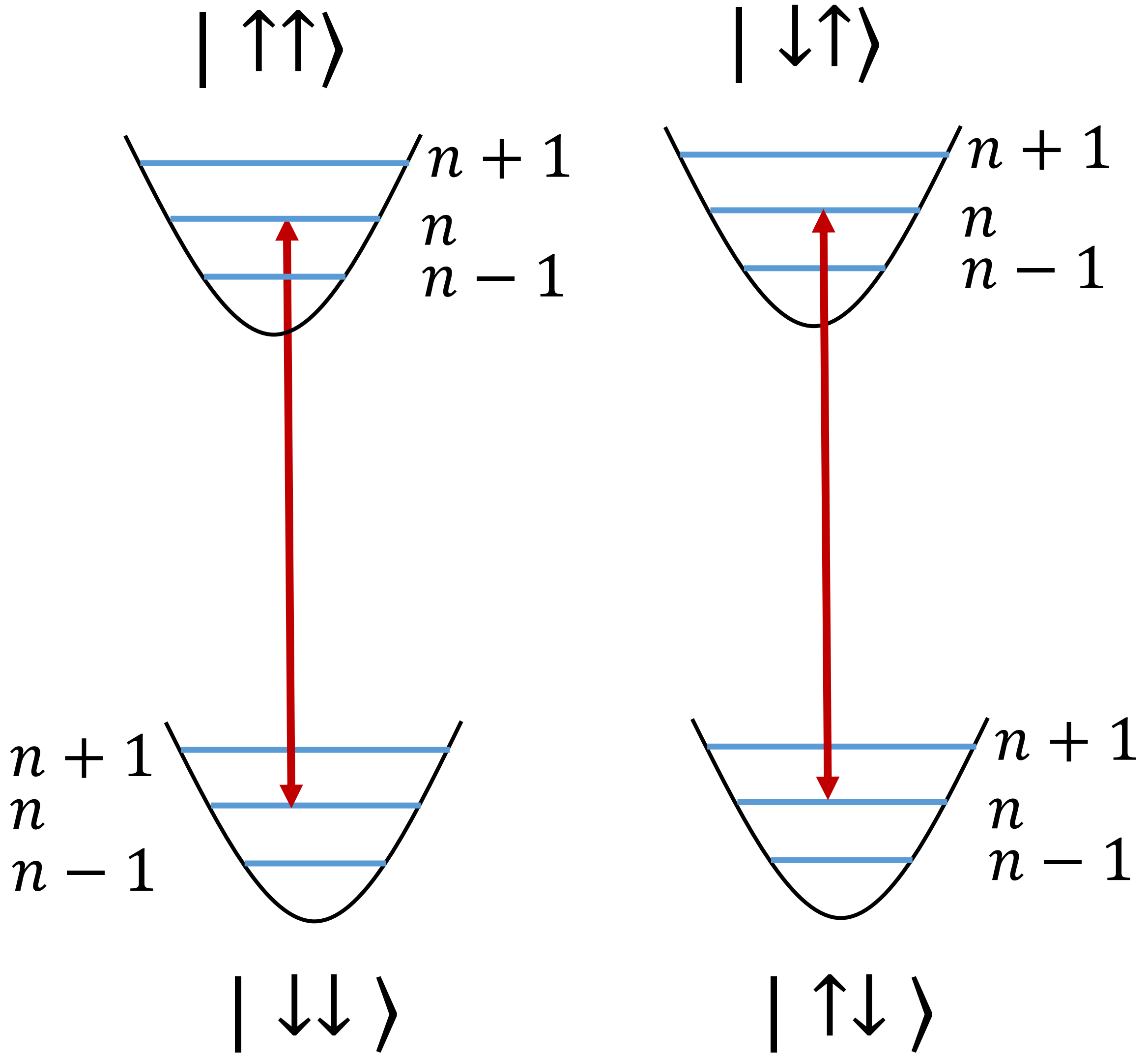
Phonon mediated spin-spin interactions





Phonon mediated spin-spin interactions

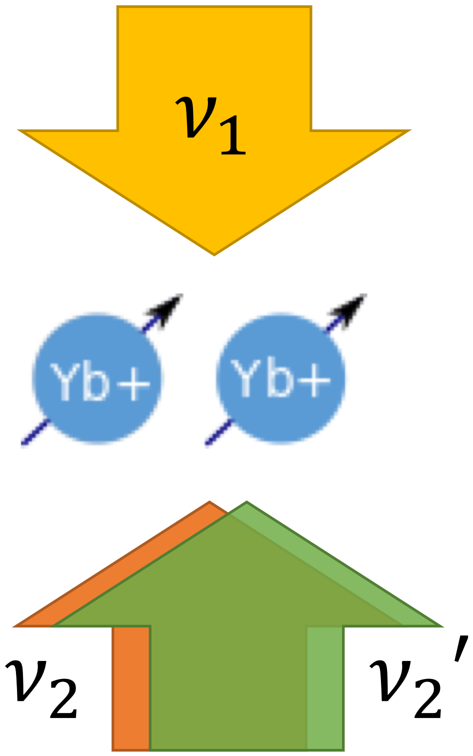




$$H_{eff} = H_{XX} = \sum_{i>j} J_{i,j} S_i^x S_j^x$$

- Cirac, Zoller **PRL** 4091 (1995)
- Molmer, Sorensen **PRL** 1835 (1999)

Phonon mediated spin-spin interactions



$$H_{XX} + B_z \sum_i S_i^z \xrightarrow{|B_z| >> |J_{i,j}|} H_{XY}$$

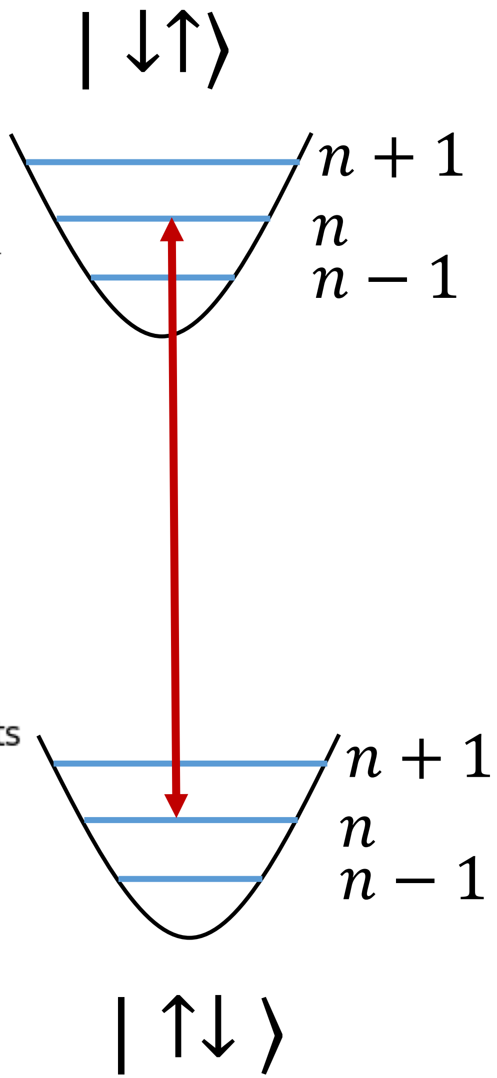
$$H_{XY} = \sum_{i<j} J_{ij} S_i^+ S_j^- + h.c.$$

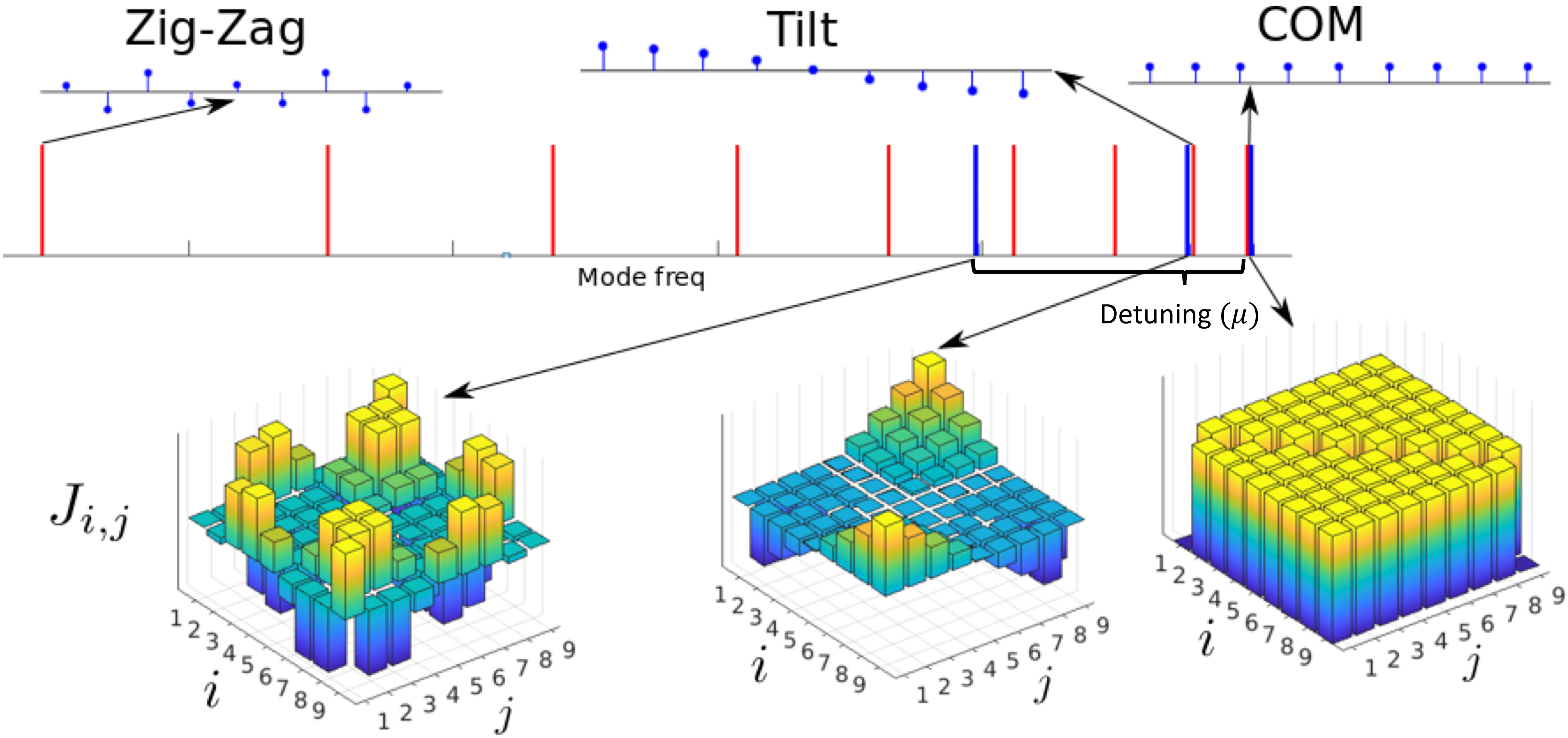
Normal mode eigenvector components

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Laser intensity over each ion

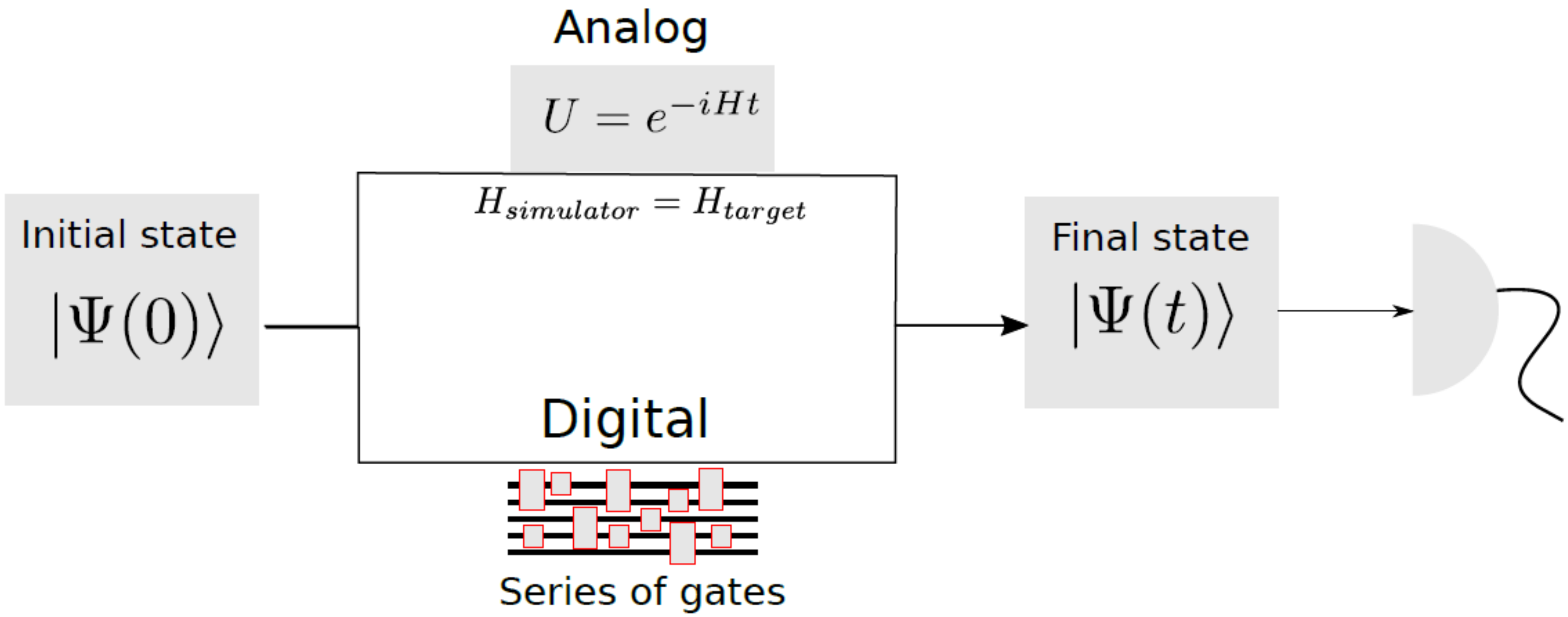
Mølmer-Sørensen detuning





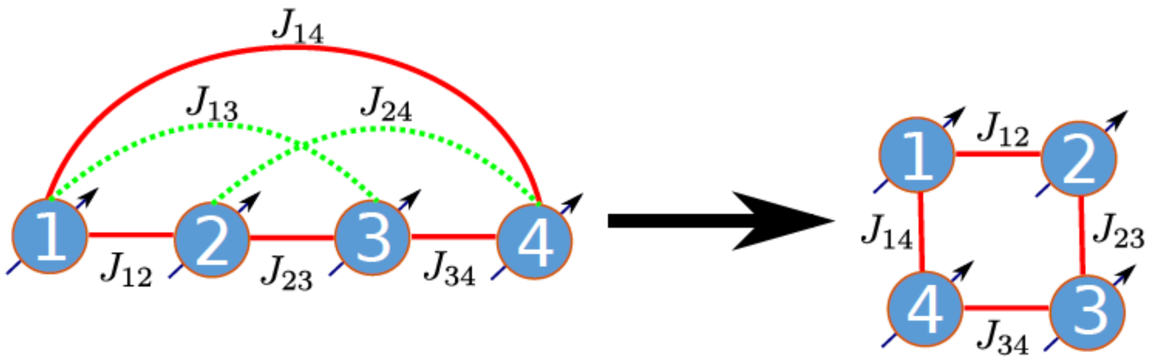
Simulate various interaction profiles by changing the detuning – restricted to only certain types of profiles

Types of Quantum simulation



Analog : Not Universal, restricted to simulation of certain types of Hamiltonians
Digital : Universal, but errors in simulation due to digitization

Hybrid simulation – Analog + Digital



Analog: Choose an interaction profile that can be engineered with global Raman beams. (Molmer-Sorensen scheme)

Digital: Supress unwanted interactions and scale other spin interactions by using single spin operations only
e.g., using laser induced site dependent AC stark shift

Hybrid simulation – Analog + Digital

Consider a chain of ions with internal flip-flop Hamiltonian and external AC Stark shift

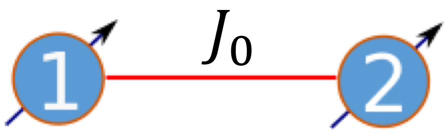
$$H_{XY} = \sum_{i<j} J_{ij} S_i^+ S_j^- + h.c. \qquad J_{i,j} = \frac{J_0}{|i-j|^\alpha} \quad \alpha = (0,3)$$

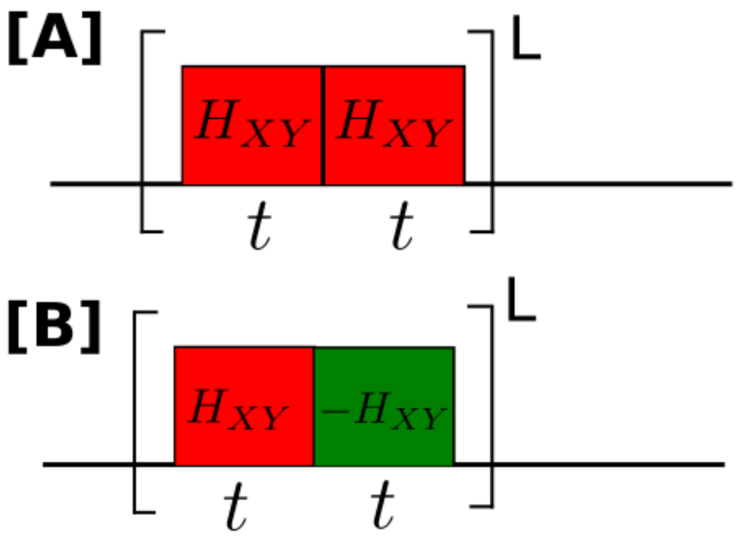
Created using a global Molmer-Sorensen scheme

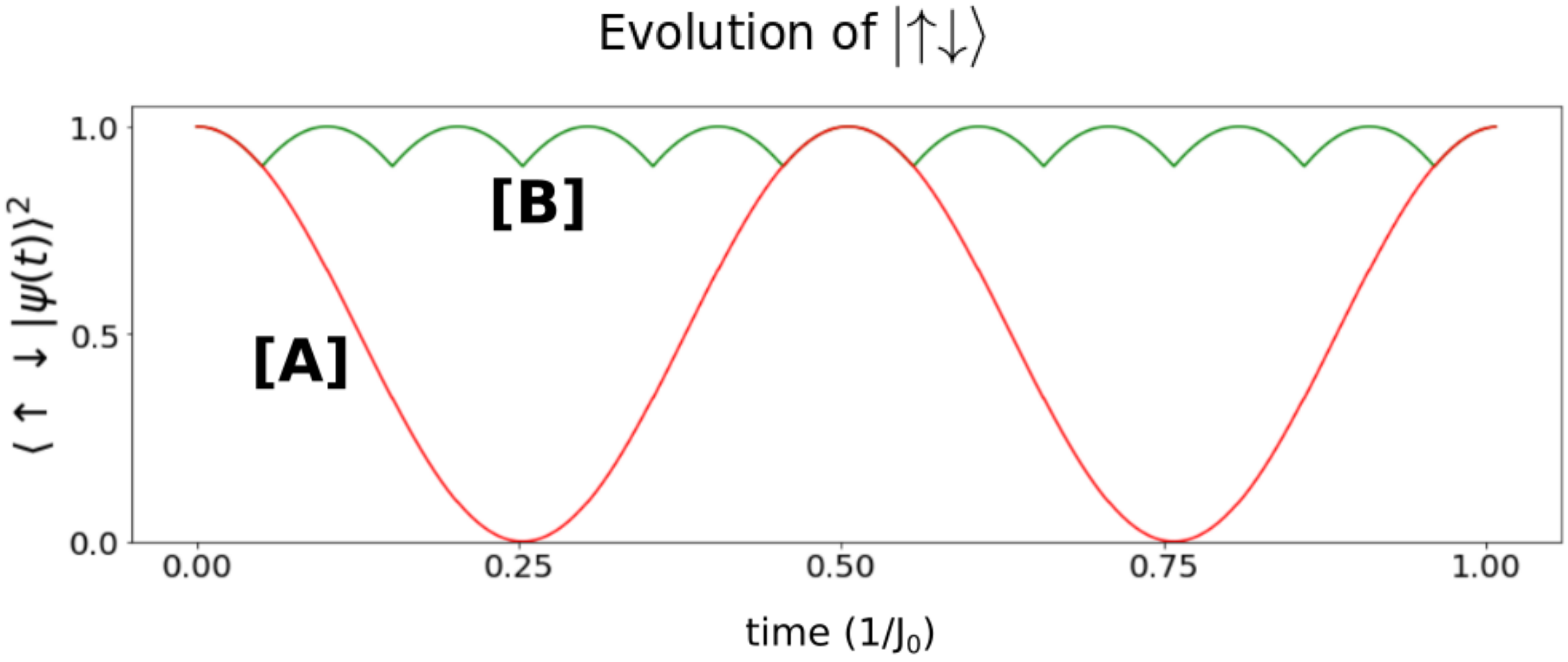
$$H_{stark} = H_Z = \sum_{i=1}^{N} \omega_i S_i^z$$

Created using an off-resonant laser beam with site dependent intensity inducing a differential AC Stark shift

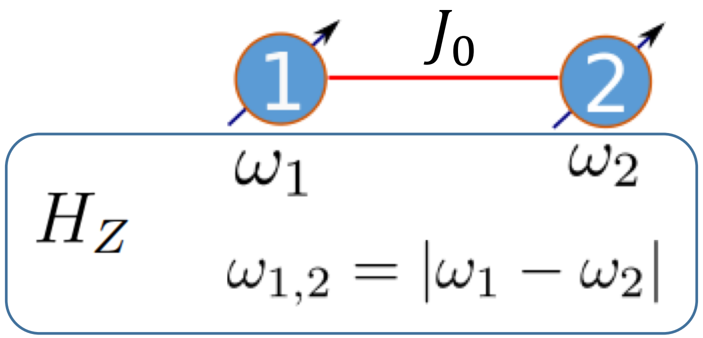
Case of 2 ions

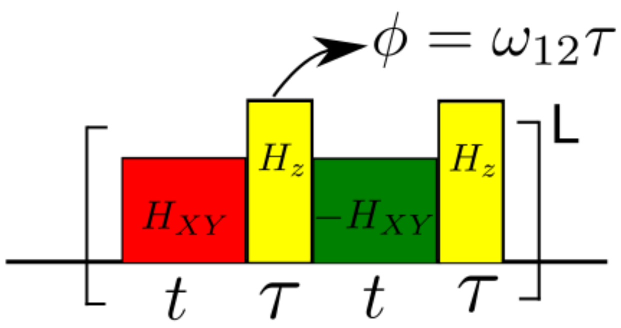




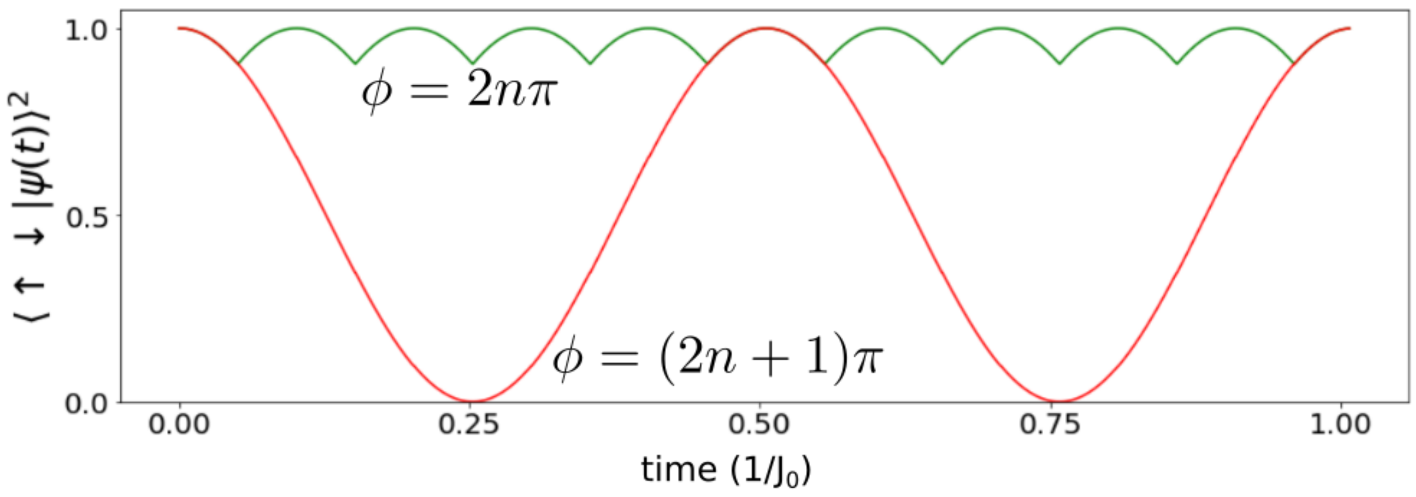


Case of 2 ions





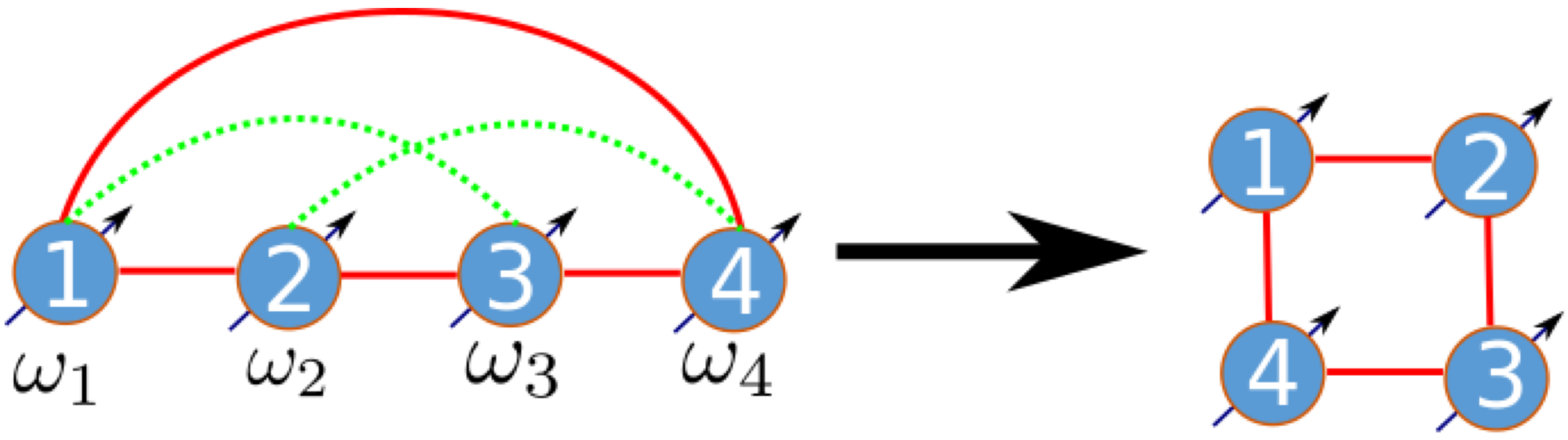
Evolution of $|\uparrow\downarrow\rangle$



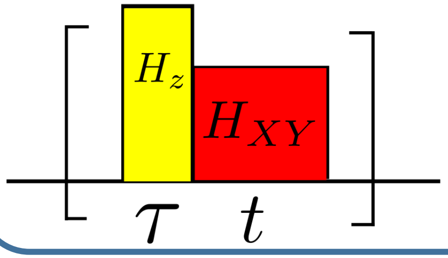
Pulse sequence cancels interaction if $\omega_{i,j}\tau = 2n\pi$

retains interaction if $\omega_{i,j}\tau = (2n+1)\pi$

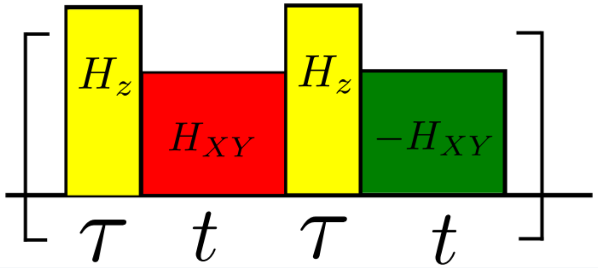
Goal



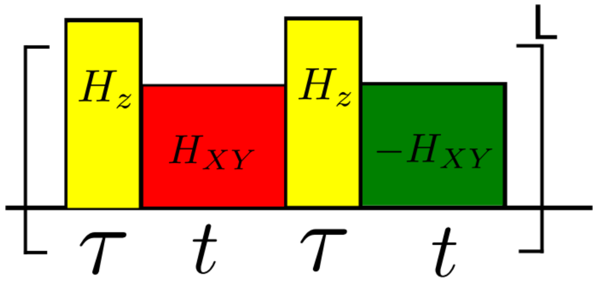
Average Hamiltonian for a sequence of pulses



$$\tilde{H}_{ff} = e^{-iH_Z\tau} H_{XY} e^{iH_Z\tau} = \sum_{i>j} J_{i,j} S_i^+ S_j^- e^{i\omega_{ij}\tau} + h.c$$



$$H_{avg} = \sum_{i>j} J_{i,j} S_i^+ S_j^- (e^{i\omega_{ij}\tau} - e^{2i\omega_{ij}\tau}) + h.c$$

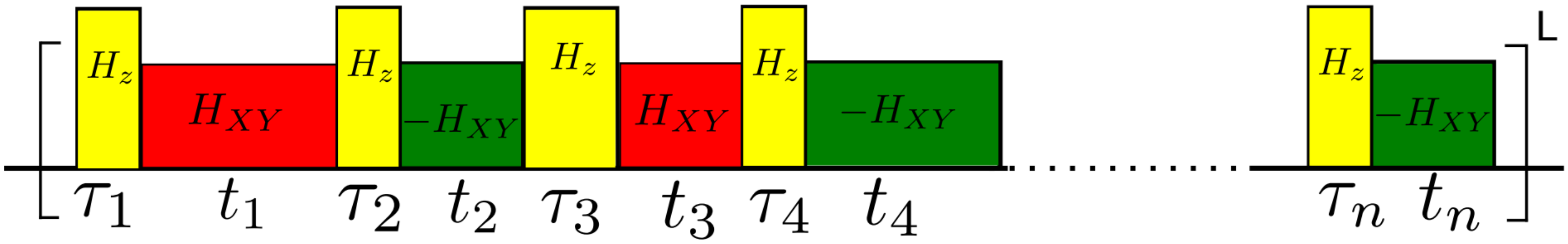


$$H_{avg} = \sum_{i>j} J'_{i,j} S_i^+ S_j^- + h.c$$

Valid if $J_0 * T_{cycle} << 1$

$$J'_{i,j} = \frac{J_{ij}}{L} * (e^{i\omega_{ij}\tau_{tot}} - e^{2i\omega_{ij}\tau_{tot}} + \ldots e^{Li\omega_{ij}\tau_{tot}})$$

Supresses the interactions (i,j) where $\omega_{ij}\tau_{tot} = 2n\pi$



$$H_{avg} = \sum_{i>j} J''_{i,j} S_i^+ S_j^- + h.c$$

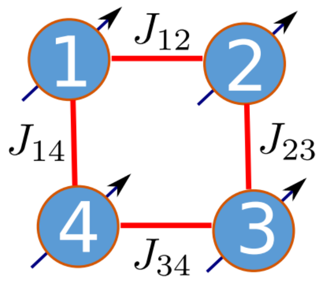
$$J''_{i,j} = \frac{J'_{i,j}}{T_{cycle}} * (t_1 e^{i\omega_{ij}\tau_1} - t_2 e^{i\omega_{ij}(\tau_1+\tau_2)} \ldots)$$

Use this to scale (also cancel) the remaining interactions

Task : Find a solution for $\{\omega_i, \tau_k, t_k\}$ to simulate 2D lattices

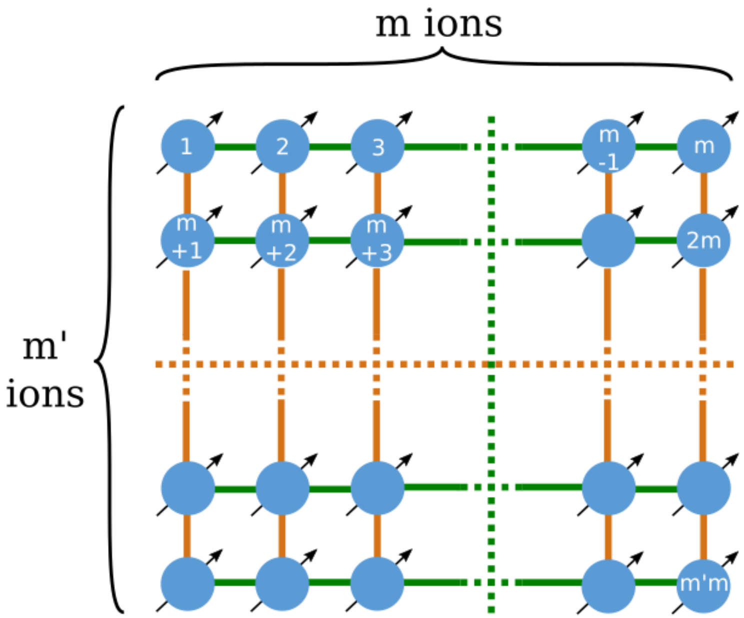
Stark shift ω_i pattern to simulate 2D lattices

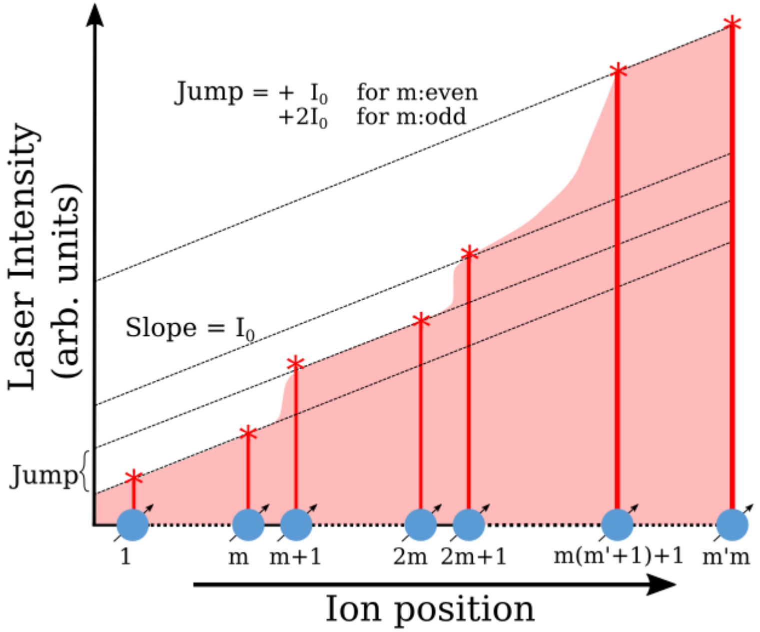
$$\begin{aligned} \text{Bond class} &= \{(1,2),(2,3),(3,4),(1,4)\} \\ \text{NoBond class} &= \{(1,3),(2,4)\} \end{aligned}$$



Find ω_i such that

$$\{\omega_{ij} \mid (i,j) \in Bond\} \cap \{\omega_{ij} \mid (i,j) \in NoBond\} = \phi$$





Construction of pulse sequence

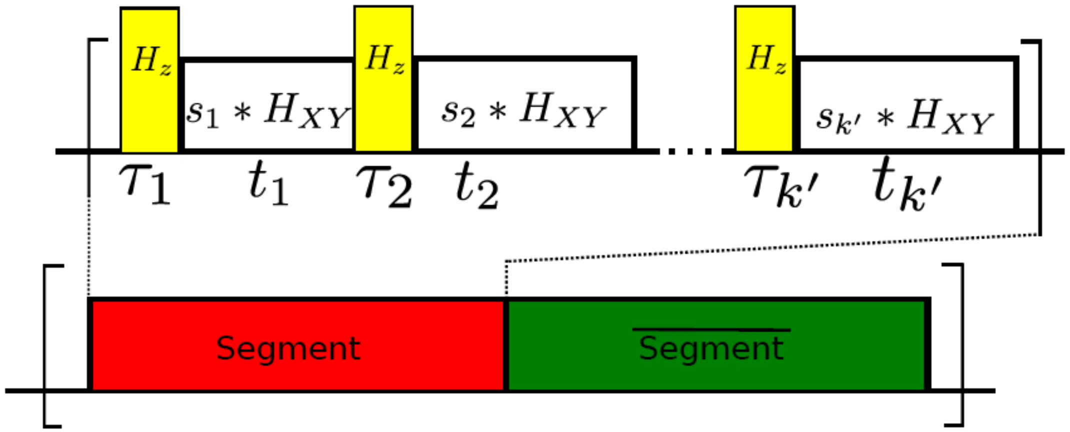
$$
\begin{aligned}
J''_{ij}(\{t_k,\tau_k\}) = F(\omega_{ij} * \tau_{tot}) &= 0 && \text{for } (i,j) \in \text{Nobond class} \\
&= 1/m^{\alpha} && \text{for } (i,j) \in \text{Bond class and } \omega_{ij} = \omega_0 \\
&= 1 && \text{for } (i,j) \in \text{Bond class and } \omega_{ij} \neq \omega_0
\end{aligned}
$$

Fit with function $G(\phi) = \sum_{l=0}^{l'} a_l * cos(iW\phi)$ obtain optimum values of $\{a_l, W\}$

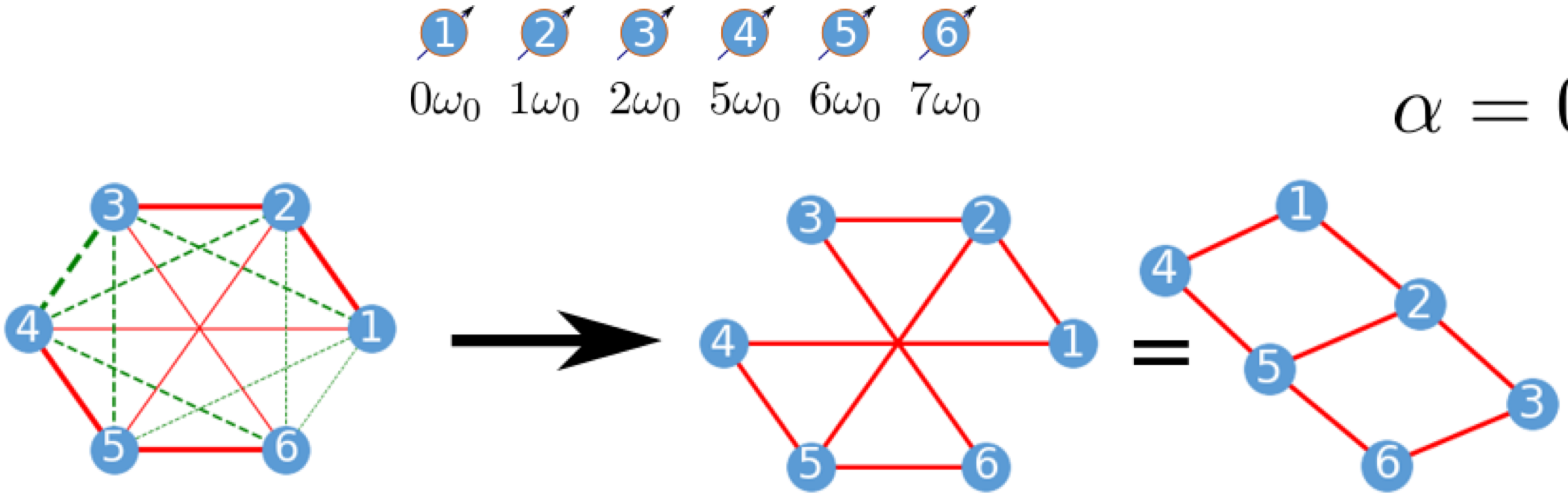
$$
\begin{aligned}
t_k &= |a_k/2| && \text{for } k = (1,2,....,l') \\
&= t_{k-l'} && \text{for } k = (l'+1,....,2l') \\
&= |a_0| && \text{for } k = 2l'+1
\end{aligned}
$$

$$
\begin{aligned}
\tau_k &= \tau_{tot} * W && \text{for } k \neq (l'+1) \\
&= \tau_{tot} - (l'-1)\tau_1 && \text{for } k = l'+1
\end{aligned}
$$

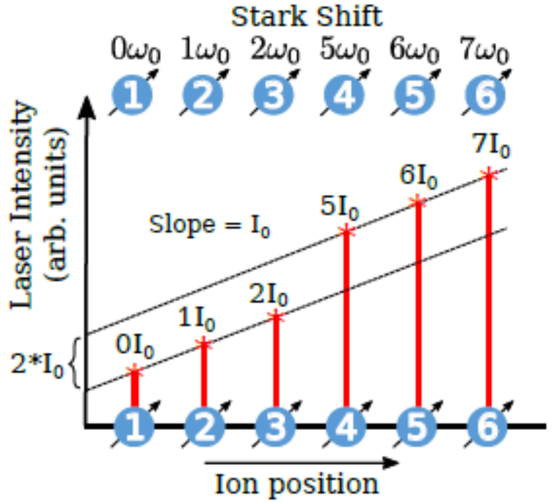
$$
\begin{aligned}
s_k &= sign(a_k) && \text{for } k = (1,2,...,l') \\
&= -s_{k-l'} && \text{for } k = (l'+1,....,2l') \\
&= -sign(a_0) && \text{for } k = 2l'+1
\end{aligned}
$$



Simulating 3x2 lattice with 6 ion chain



$\alpha = 0.2$



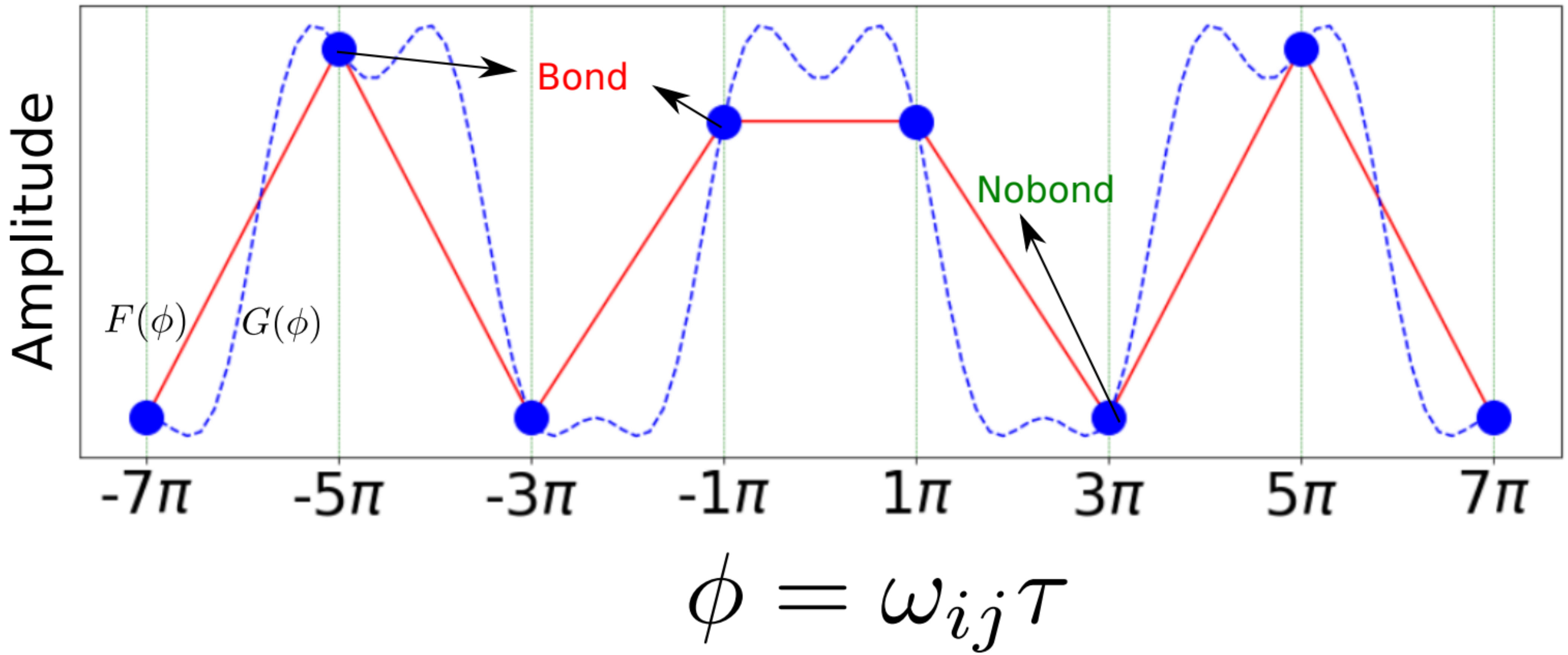
Bond class

(1, 4), (1, 2),
(2, 5), (2, 3),
(3, 6), (4, 5), (5, 6)

NoBond class

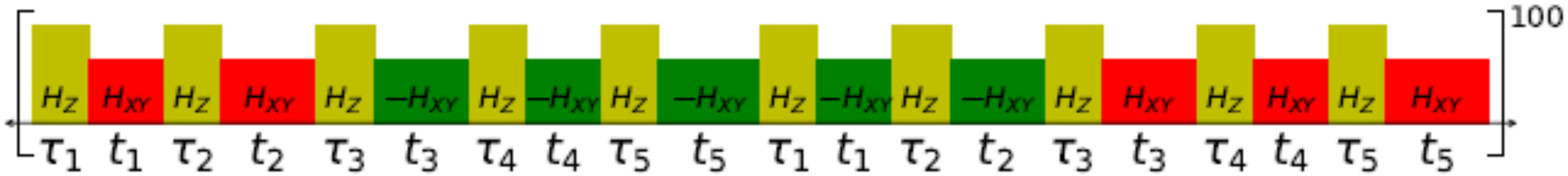
(1, 6), (3, 4),
(2, 4), (1, 3), (2, 6),
(1, 5), (3, 5), (4, 6)

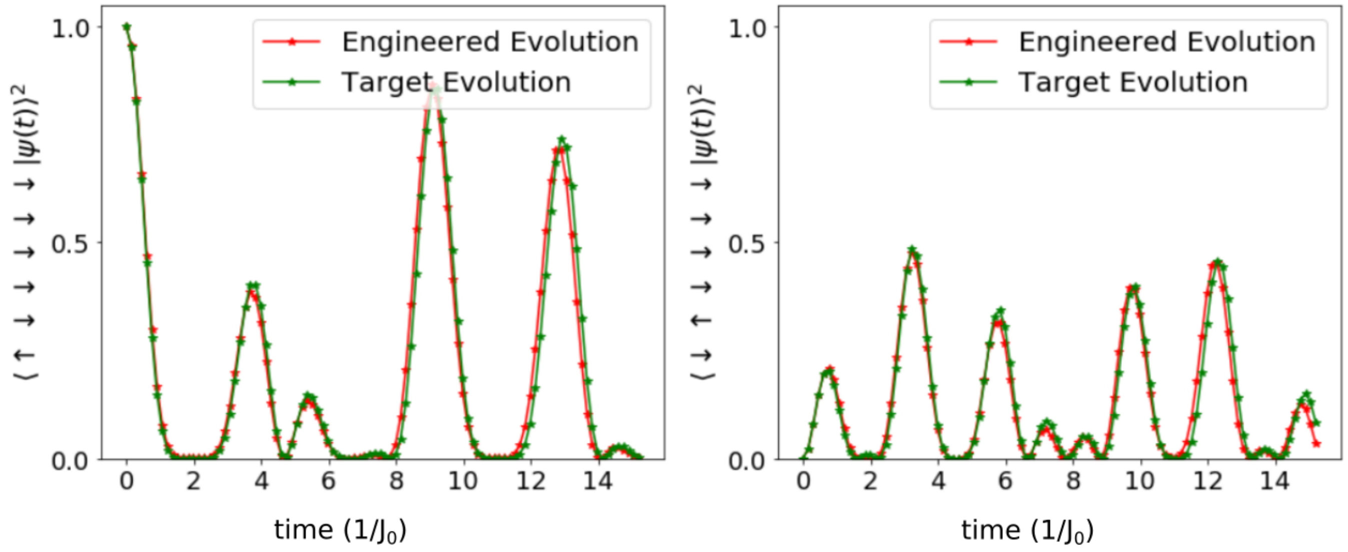
Cancelled by J'_{ij}

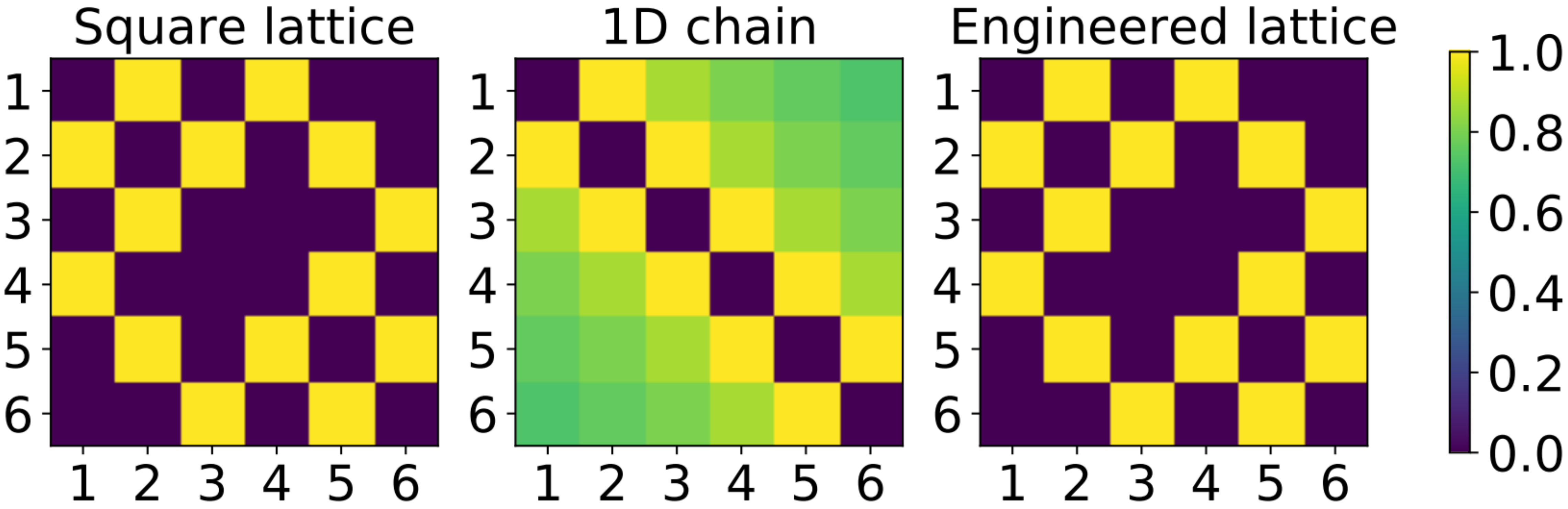


Bond
Nobond
Amplitude
$F(\phi)$
$G(\phi)$
-7π
-5π
-3π
-1π
1π
3π
5π
7π
$\phi = \omega_{ij}\tau$

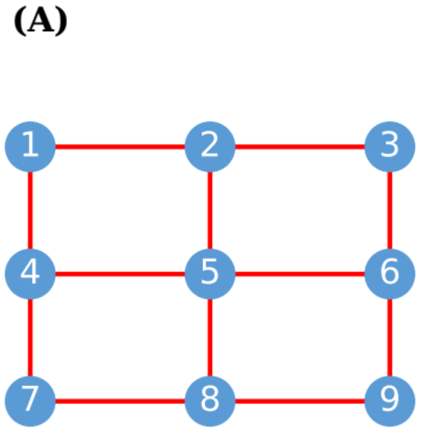
	1	2	3	4	5
$\tau(\mu s)$	6.283	6.283	6.283	6.283	6.283
$t(\mu s)$	2.989	14.961	14.961	2.989	26.055
$sign$	+1	+1	-1	-1	-1

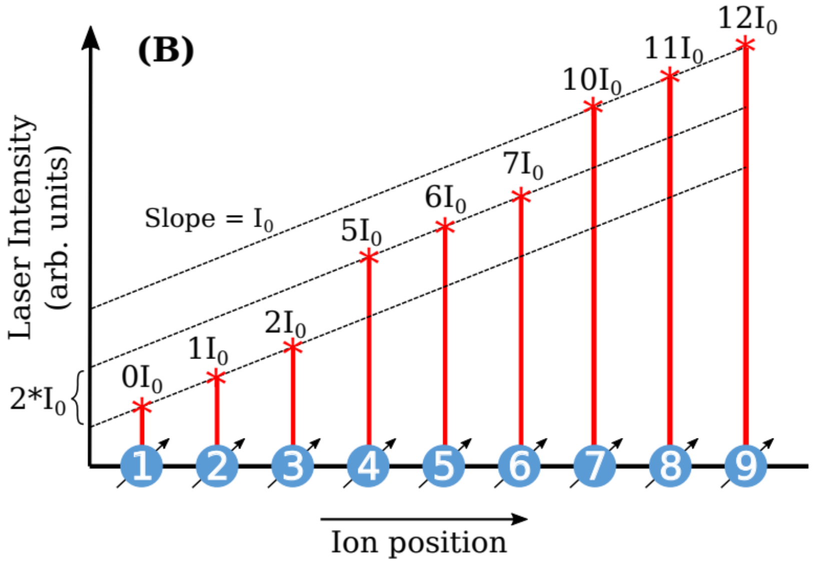





Square lattice
1D chain
Engineered lattice
1
2
3
4
5
6
1
2
3
4
5
6
1.0
0.8
0.6
0.4
0.2
0.0

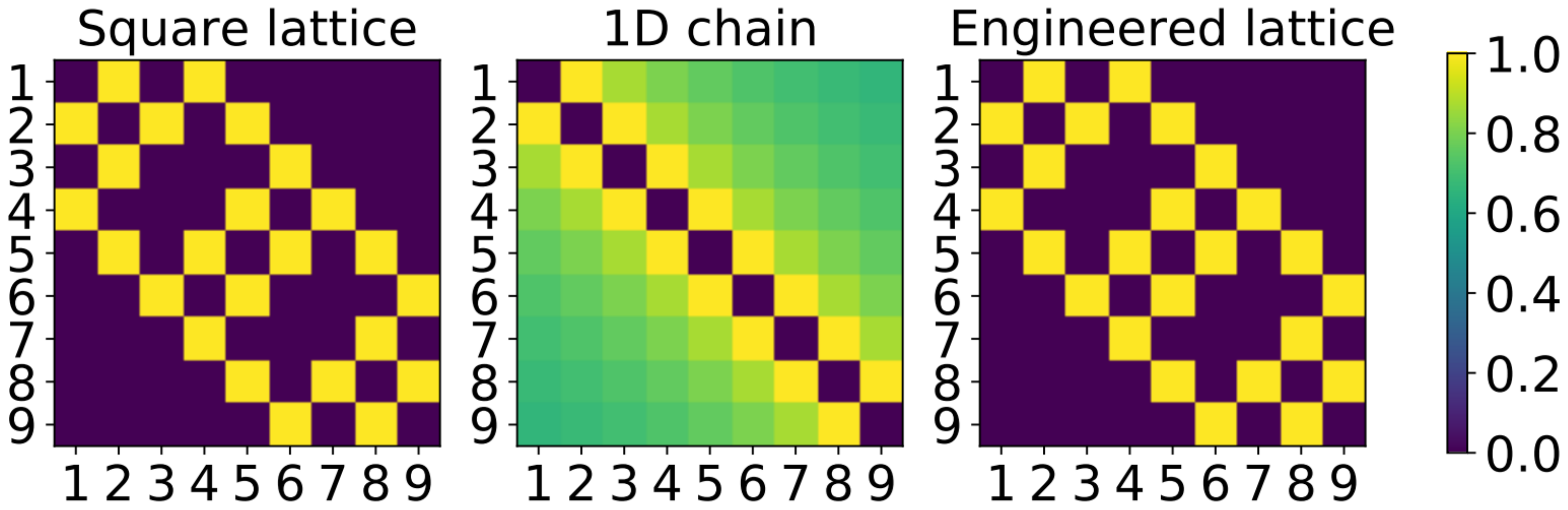
3x3 lattice with 9 ions



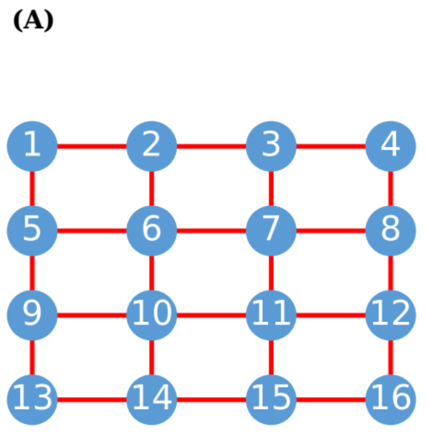


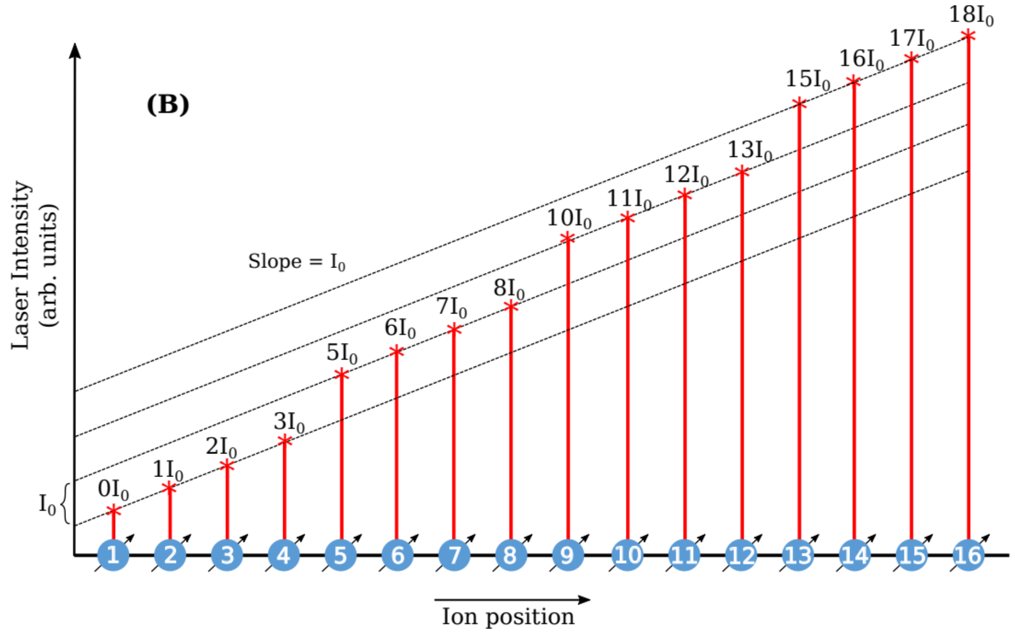
Fit parameters

W	a_0	a_1	a_2	a_3	a_4
0.1	0.360	0.305	-0.140	0.188	0.499



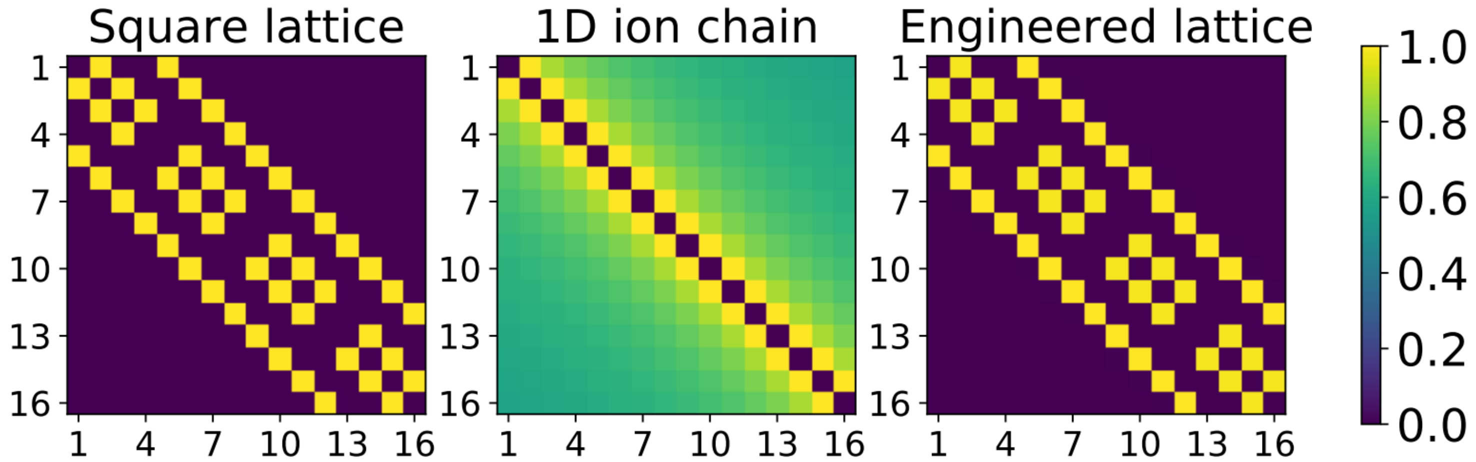
4x4 lattice with 16 ions



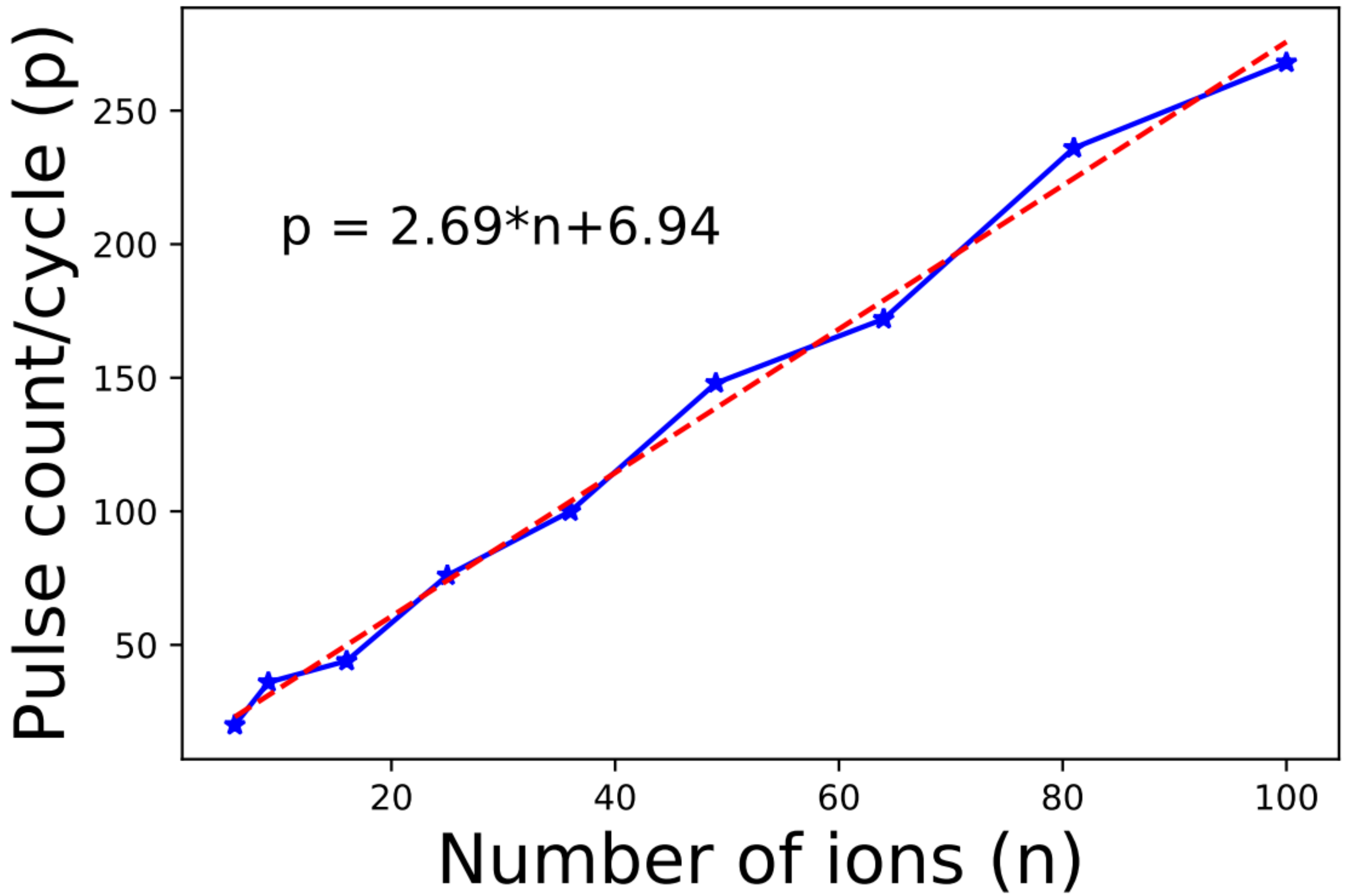


Fit parameters

W	a_0	a_1	a_2	a_3	a_4	a_5
0.083	0.293	0.33	-0.07	-0.057	0.293	0.387



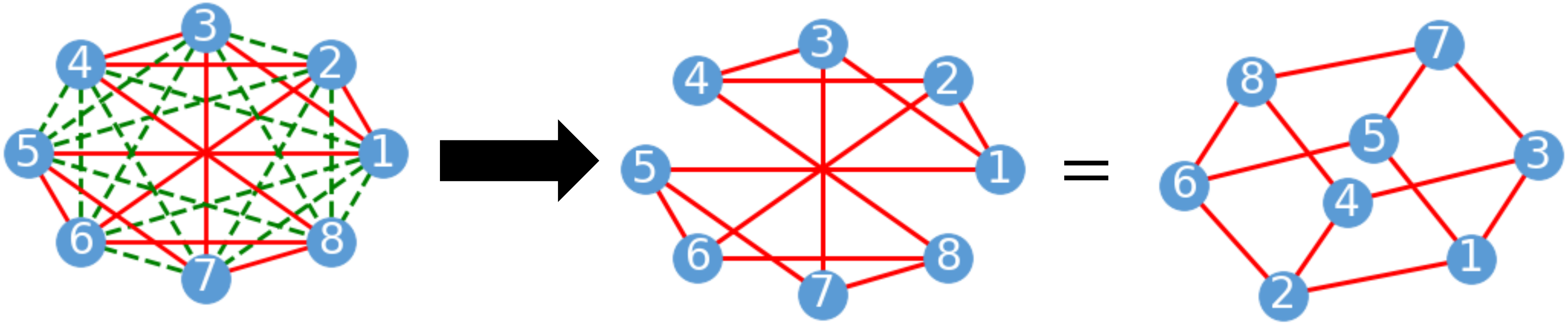
Scaling with the number of ions

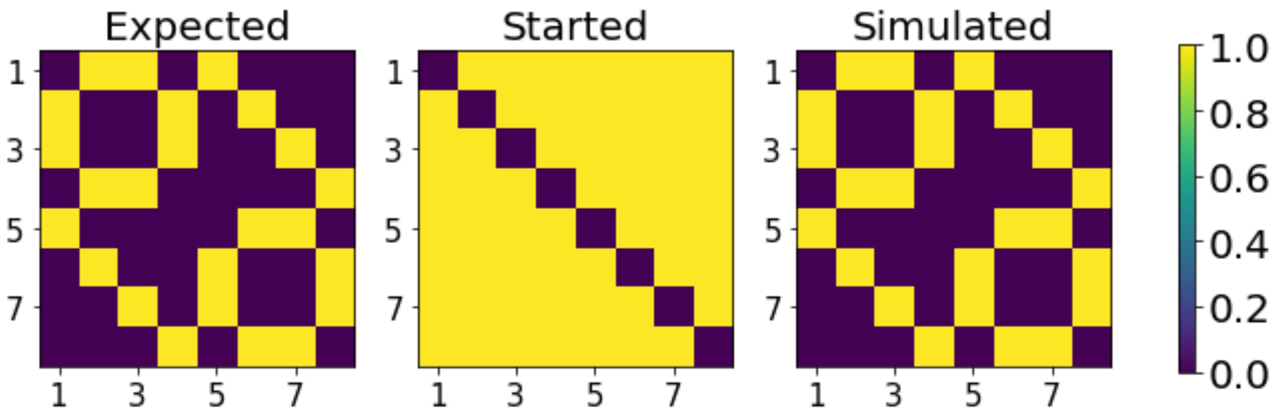


For a target 2D square lattice

Extension to 3D lattice

2x2x2 lattice with 8 ions $\alpha = 0$





Summary and Outlook

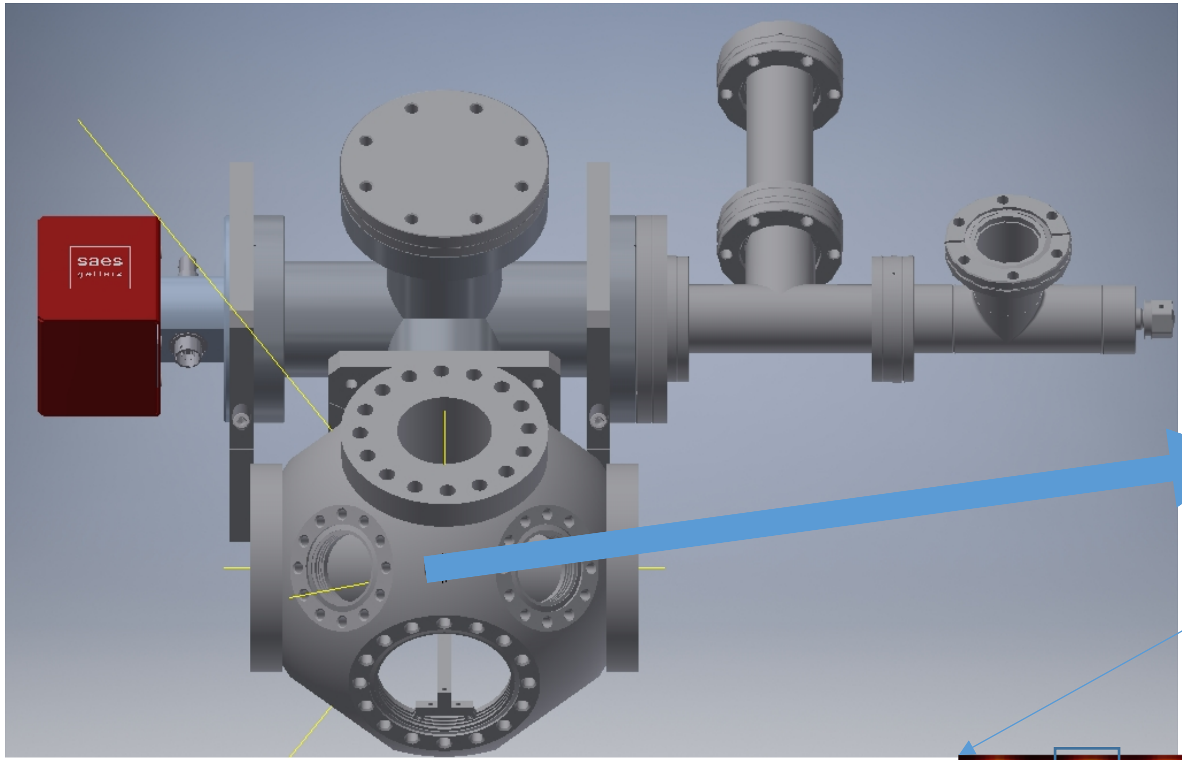
- Hybrid quantum simulation protocol to simulate 2D lattices for the case of 6, 9, 16 ions
- This protocol is scales linearly in number of pulses and stark shift gradient

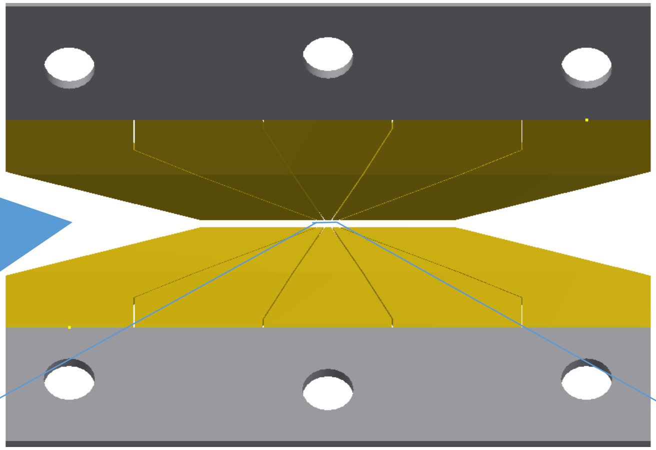
- Can be used to simulate different geometries of spin graphs
- Explore additional control by dynamically changing Stark gradients

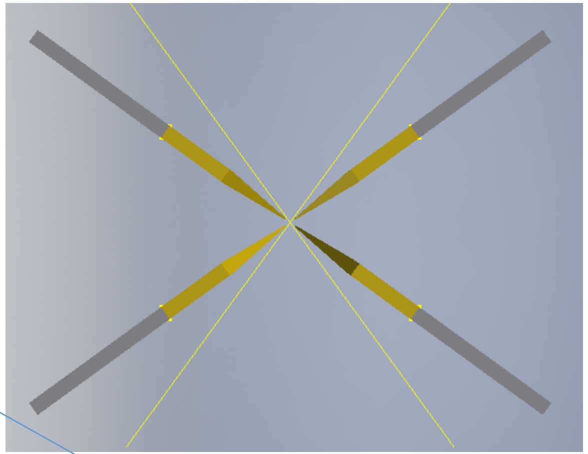
Part -2

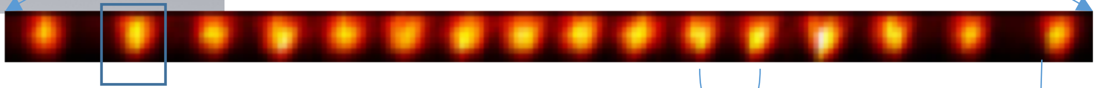
Laser frequency stabilization

$^{171}Yb^{+}$ Ion Quantum Simulator









$\sim 2\mu m$

CCD image of ions
University of Maryland/JQI
ion group

$\uparrow$ $|F = 1, m_F = 0\rangle$

$^2S_{1/2}$

$\downarrow$ $|F = 0, m_F = 0\rangle$

$^{171}Yb^{+}$Qubit

Long coherence times > 10 min
Ye Wang et al *Nature Photonics* **11**, 646–650 (2017)

Trapped ion Quantum Simulator

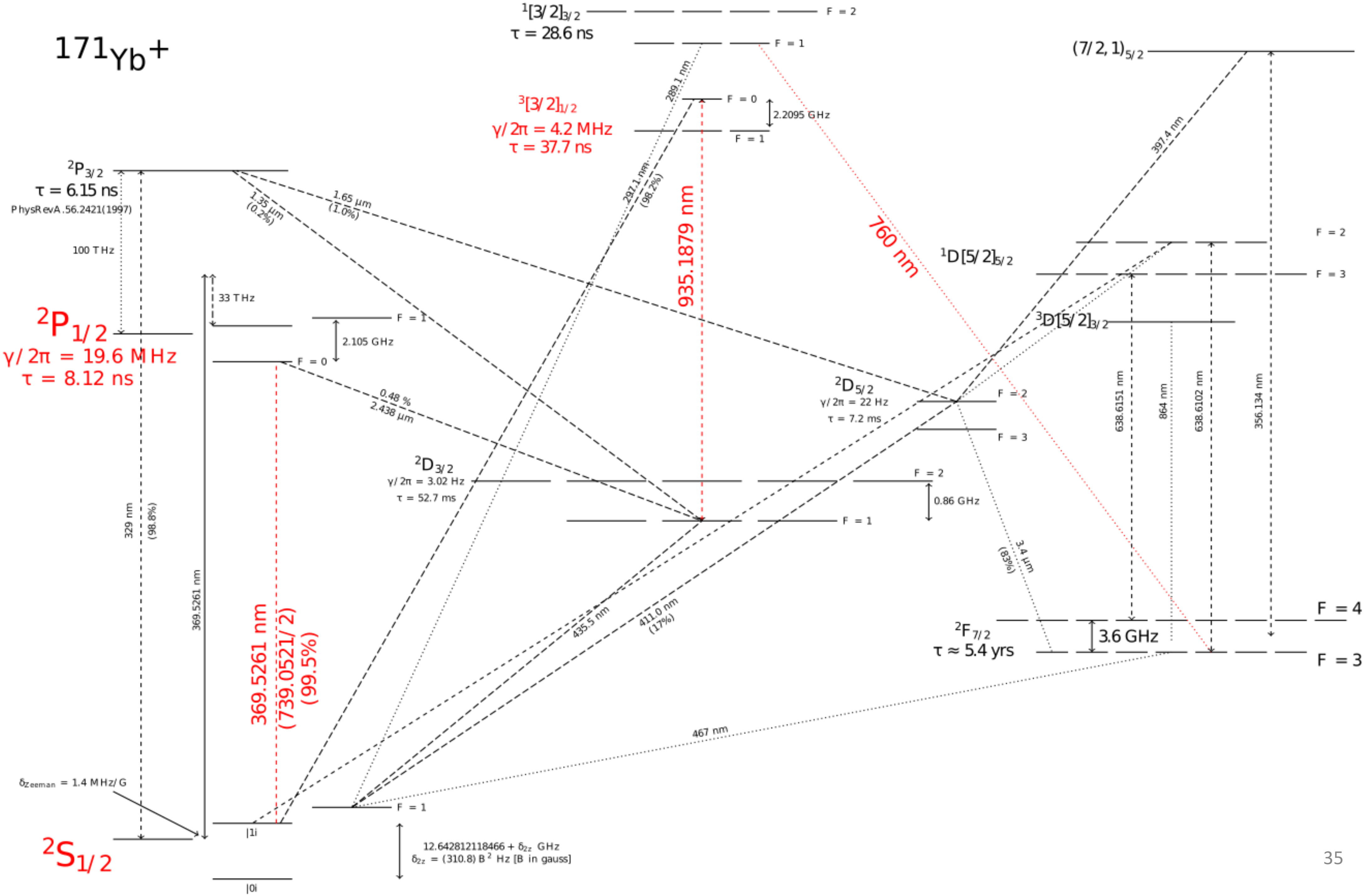
TRAP → PREPARE → MANIPULATE → DETECT

- Cool the ions to motional ground stata using Laser cooling
- Optically pump ions to ground state

Challenge

- Frequency stabilize multiple lasers

Time



$^{171}Yb^+$
$^2P_{3/2}$
τ = 6.15 ns
PhysRevA.56.2421(1997)
100 THz
33 THz
$^2P_{1/2}$
γ/2π = 19.6 MHz
τ = 8.12 ns
F = 1
F = 0
2.105 GHz
329 nm
(98.8%)
369.5261 nm
369.5261 nm
(739.0521/2)
(99.5%)
$δ_{Zeeman}$ = 1.4 MHz/G
$^2S_{1/2}$
|1i
|0i
F = 1
12.642812118466 + $δ_{zz}$ GHz
$δ_{zz}$ = (310.8) B^2 Hz [B in gauss]
1.35 μm
(0.2%)
1.65 μm
(1.0%)
0.48 %
2.438 μm
$^1[3/2]_{3/2}$
τ = 28.6 ns
F = 2
F = 1
289.1 nm
$^3[3/2]_{1/2}$
γ/2π = 4.2 MHz
τ = 37.7 ns
F = 0
F = 1
2.2095 GHz
297.1 nm
(98.2%)
935.1879 nm
760 nm
$^2D_{3/2}$
γ/2π = 3.02 Hz
τ = 52.7 ms
F = 2
F = 1
0.86 GHz
435.5 nm
411.0 nm
(17%)
467 nm
$^2D_{5/2}$
γ/2π = 22 Hz
τ = 7.2 ms
F = 2
F = 3
3.4 μm
(83%)
$(7/2, 1)_{5/2}$
397.4 nm
$^1D[5/2]_{5/2}$
F = 2
F = 3
$^3D[5/2]_{3/2}$
638.6151 nm
864 nm
638.6102 nm
356.134 nm
$^2F_{7/2}$
τ ≈ 5.4 yrs
F = 4
F = 3
3.6 GHz

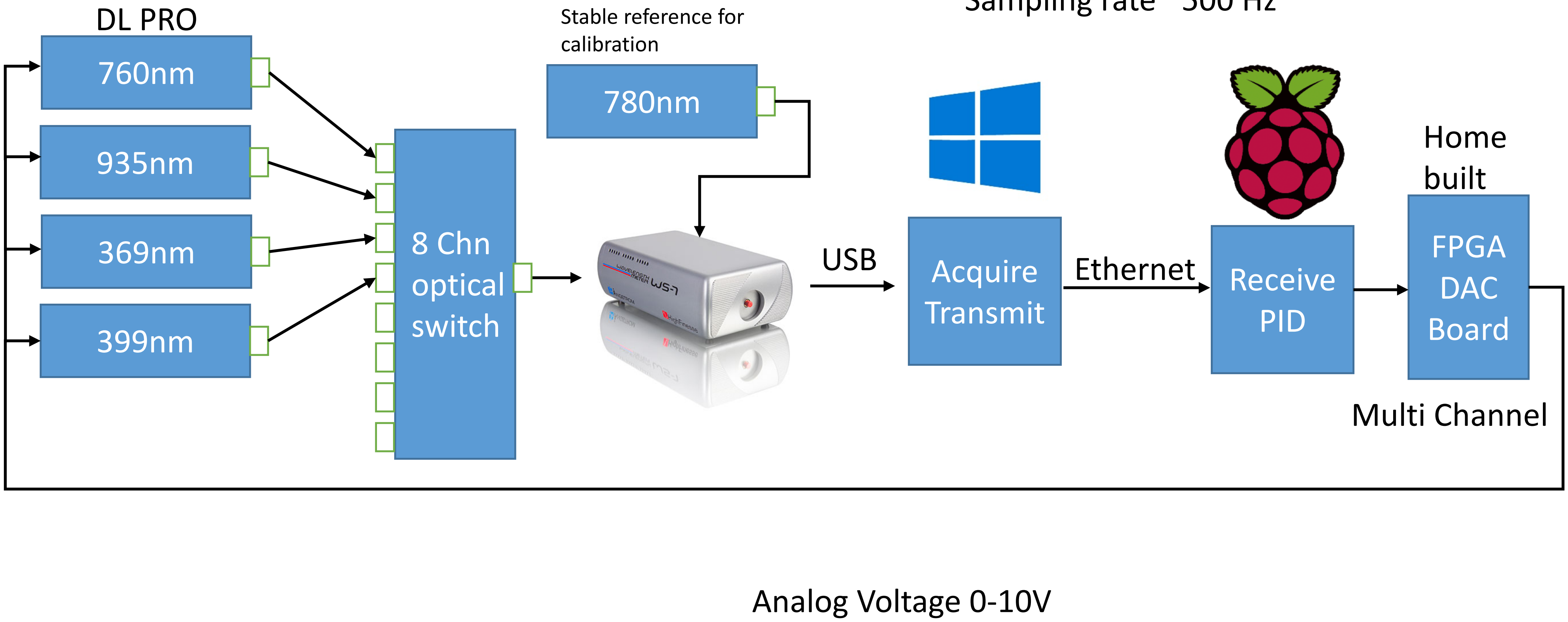
Frequency stabilization of lasers

- Stabilize lasers against drift due to ambient thermal and pressure fluctuations
- Line width of transitions order of few MHz
- No good atomic frequency reference for ions

- Solutions:
  - Laser lock based on Commercial Wavemeter
  - Lock based on in-house scanning Fabry Perot cavity

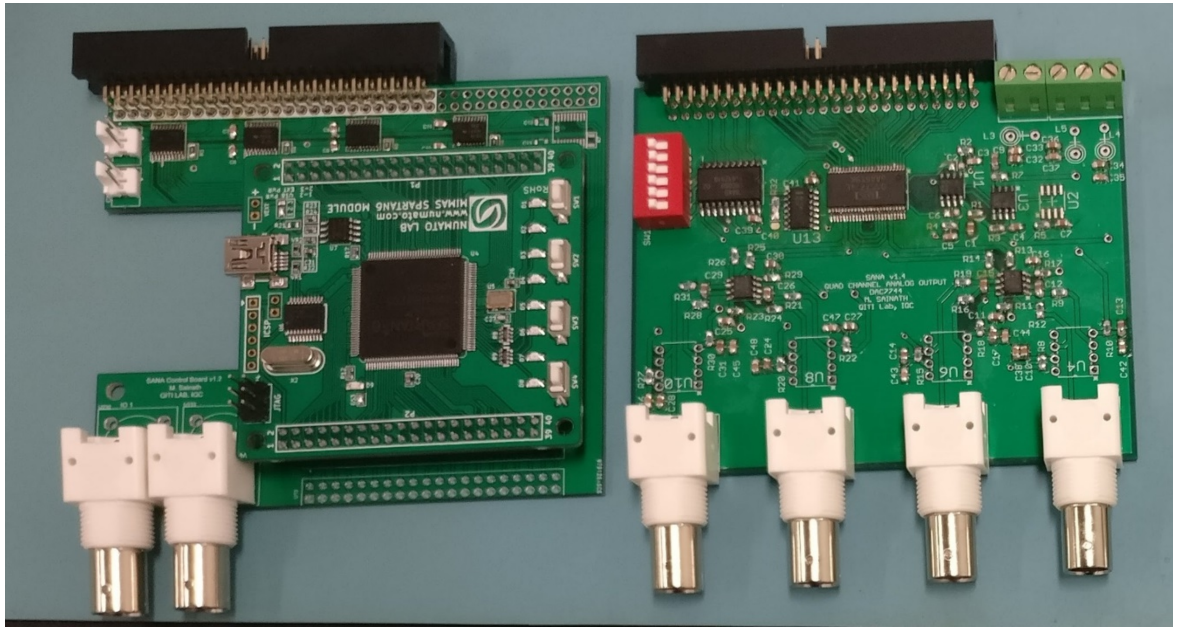
Wavemeter lock - scheme

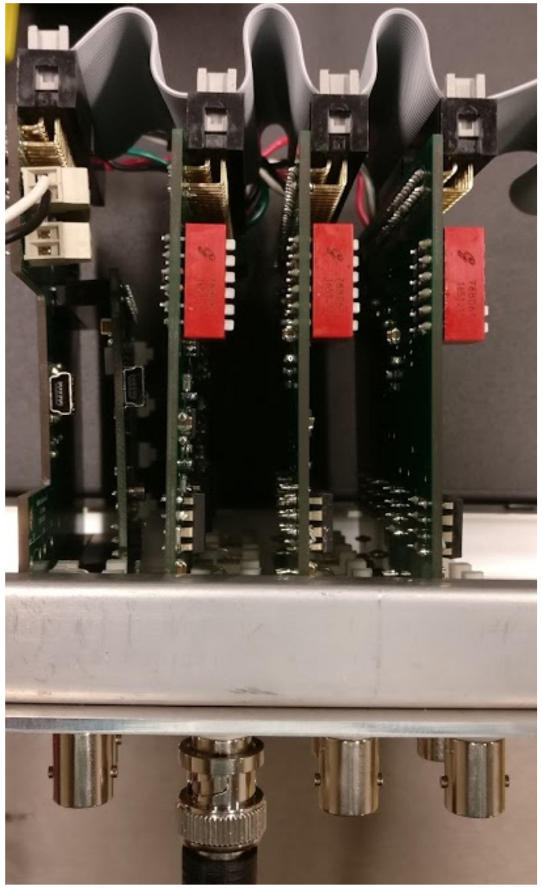
HighFinesse WS7 Wavemeter:
Based on Fizeau Interferometer
Range: 330 – 1100nm
Accuracy: 60 MHz
Sampling rate ~500 Hz



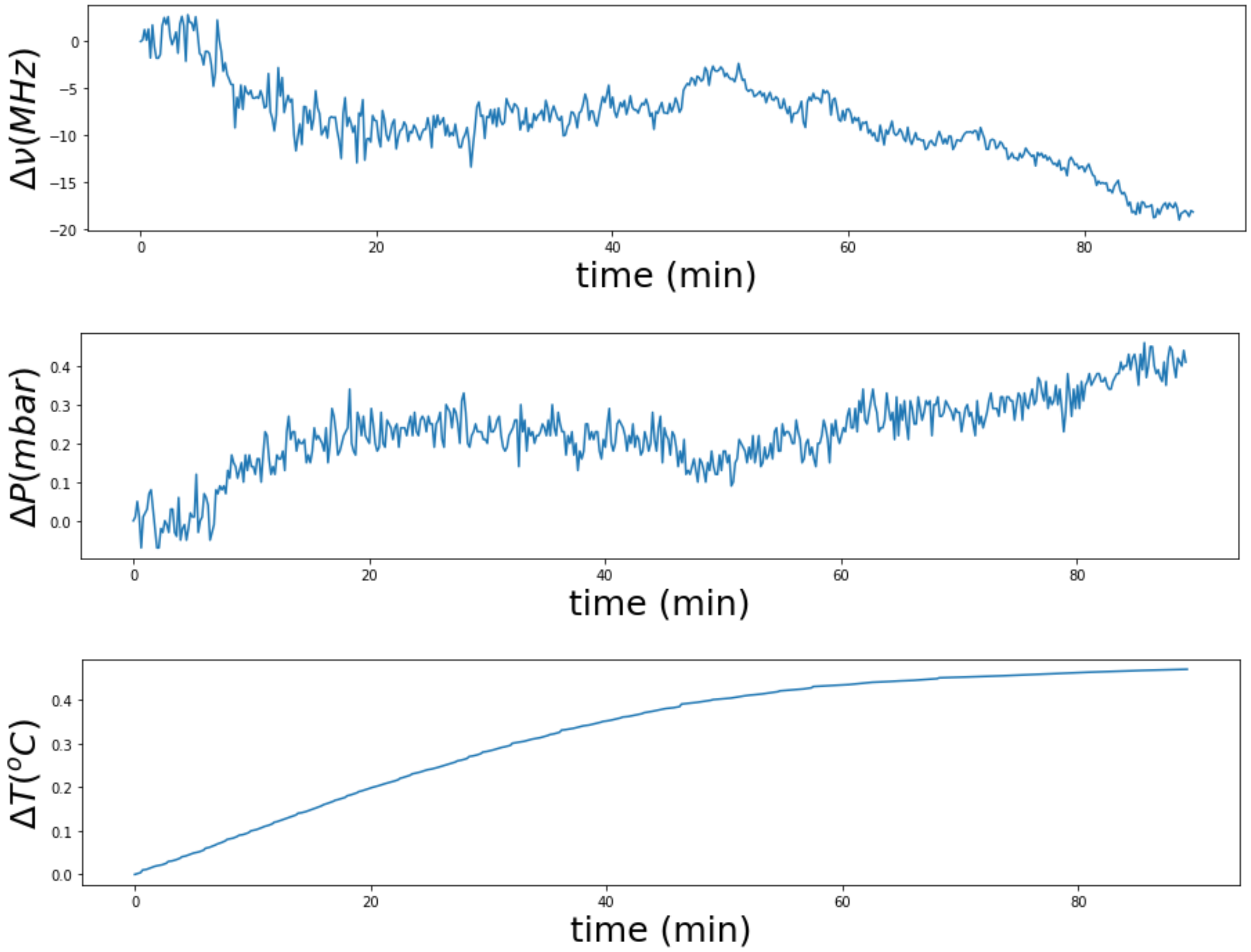
Analog output board

DAC7744: 4 channel 100 ksps 16bit
Numato Mimas FPGA board: Xilinx Spartan 6 LX9
Each board has 4 Analog output channels and has unique 6 bit address set by a DIP switch



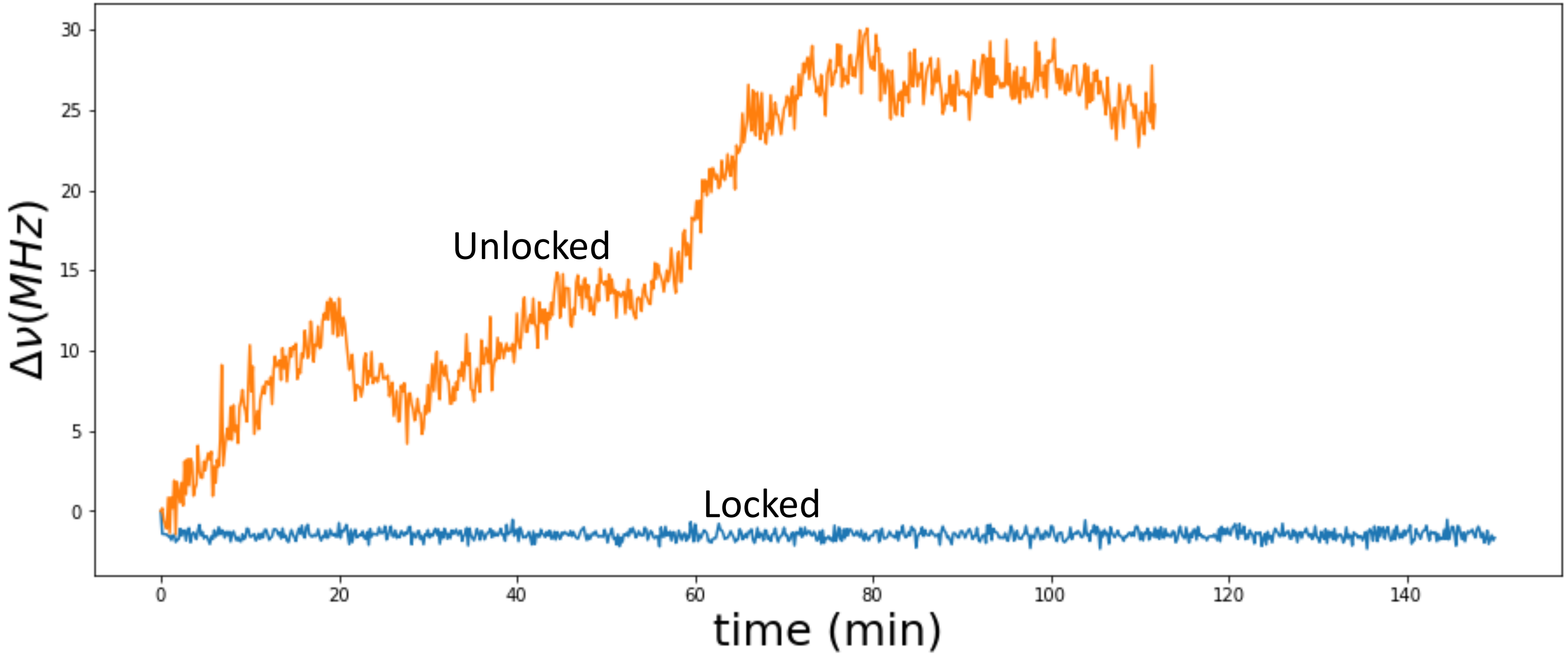


Measurements



Pressure and temperature measured from wavemeter

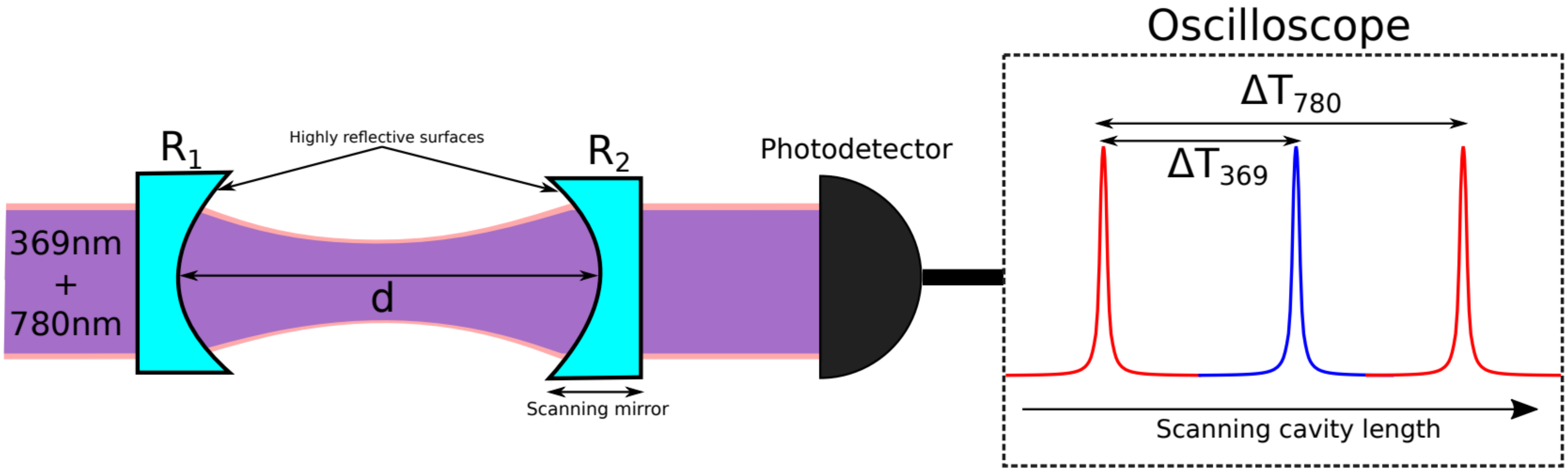
Measurements



DLPRO 935nm laser

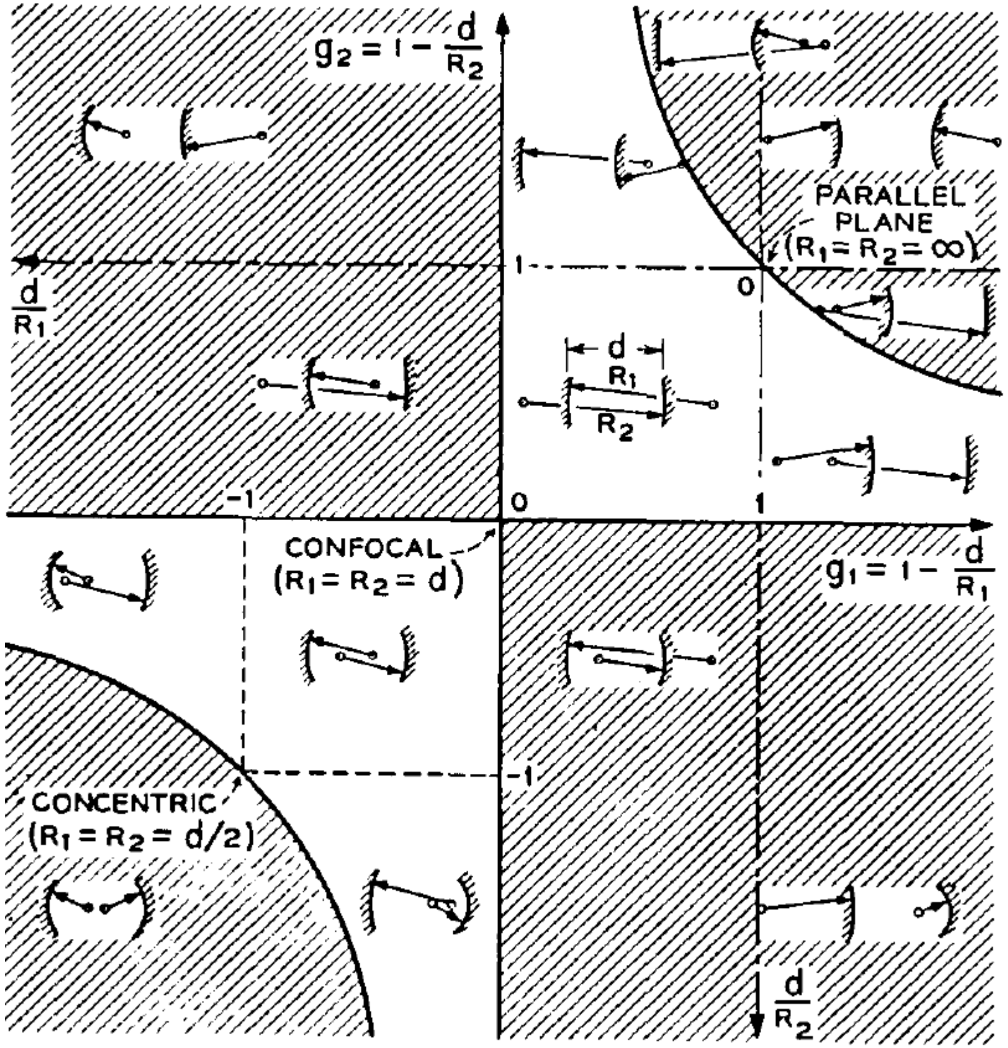
Limited by the resolution,
accuracy and response time
Of the wavemeter

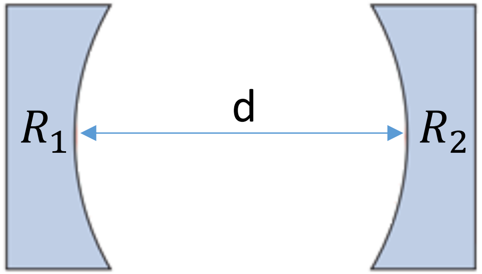
Cavity based frequency lock



Feedback laser to keep $\Delta T_{369}/\Delta T_{780}$ constant

Stability condition for the cavity





$$R_1 = R_2 = 150mm$$

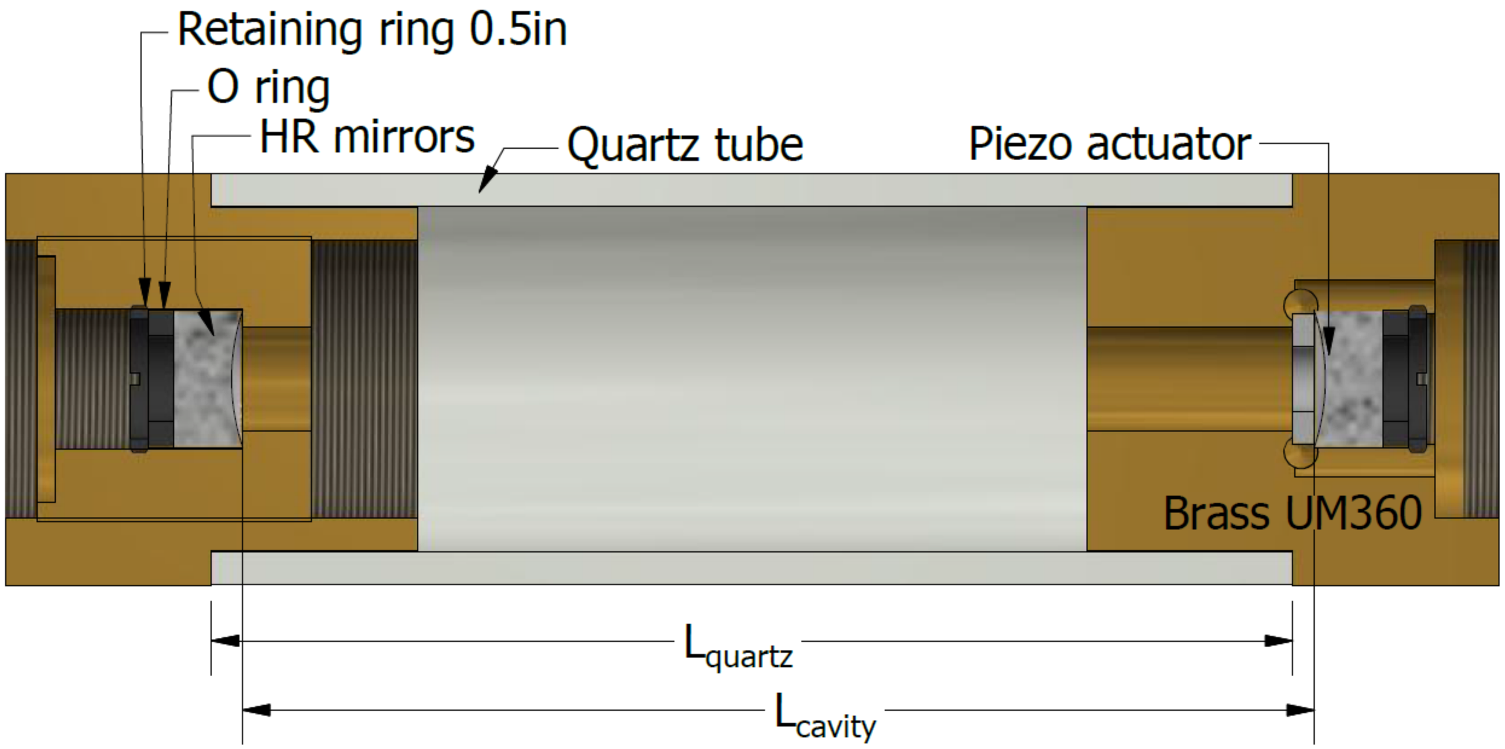
Define $g_i = \left(1 - \frac{d}{R_i}\right)$ $i = 1,2$

Cavity stability condition: $0 \leq g_1 * g_2 \leq 1$

We set $d \sim 100\ mm$ $FSR \sim 1.5GHz$

Kogelnik, H., & Li, T. (1966). Applied optics, 5(10), 1550-1567.

Cavity construction



Concave mirrors ROC=150 mm
HR Mirrors R>99.5% @ 369nm - 925nm

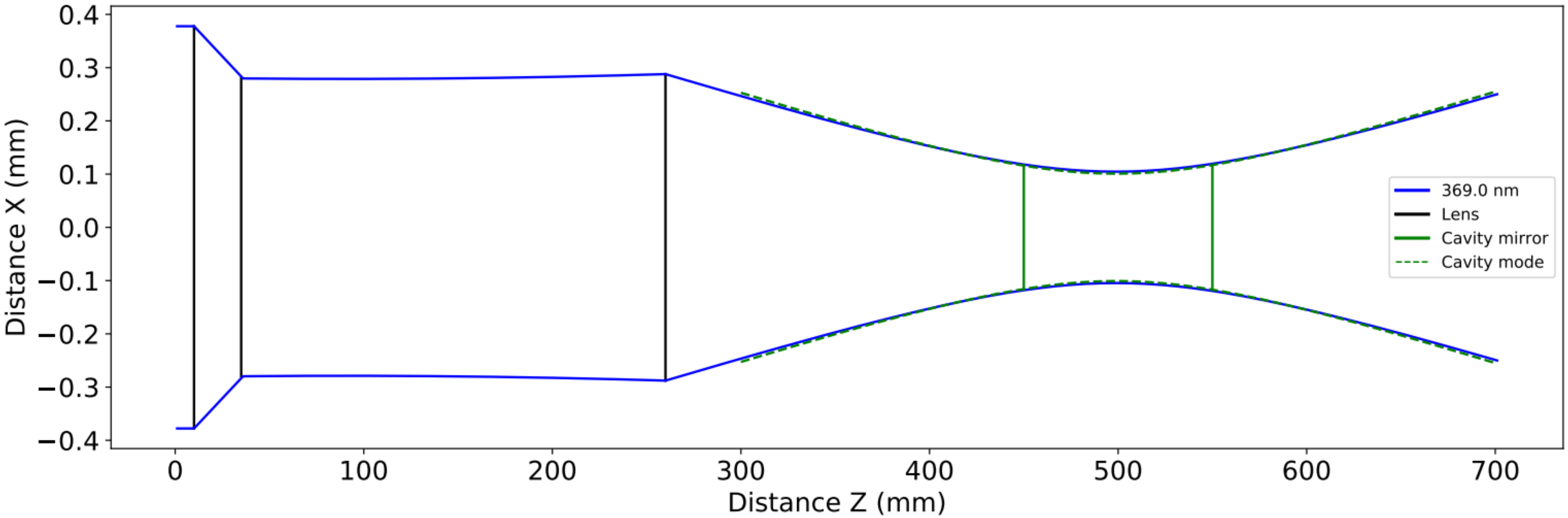
Expected Finesse > 600

Endcaps: Brass (360 UM) (CTE: ~20ppm/°C)
Spacer : Quartz (CTE: ~0.5ppm/°C)

Dimensions are chosen to minimize thermal drifts

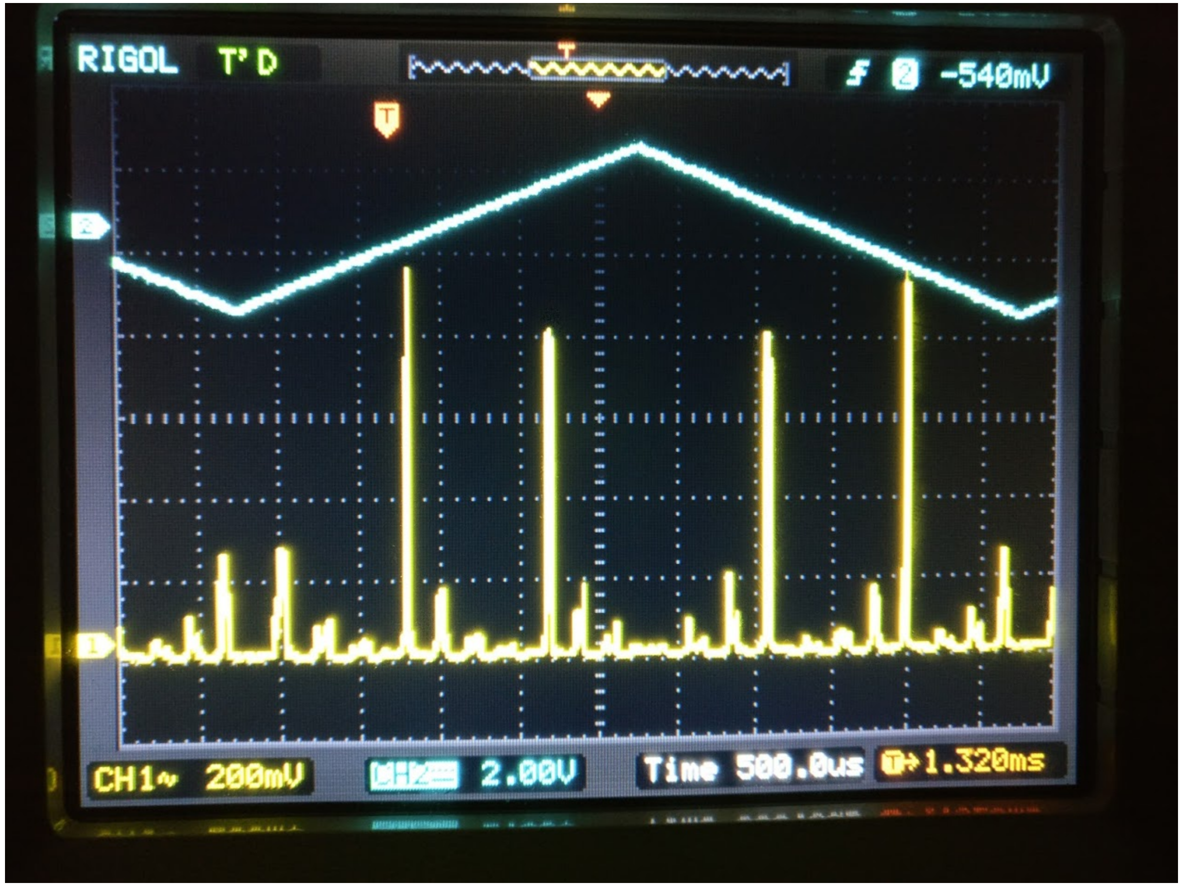
Barry, J Ph.D. thesis, Yale University (2013).

Cavity mode matching



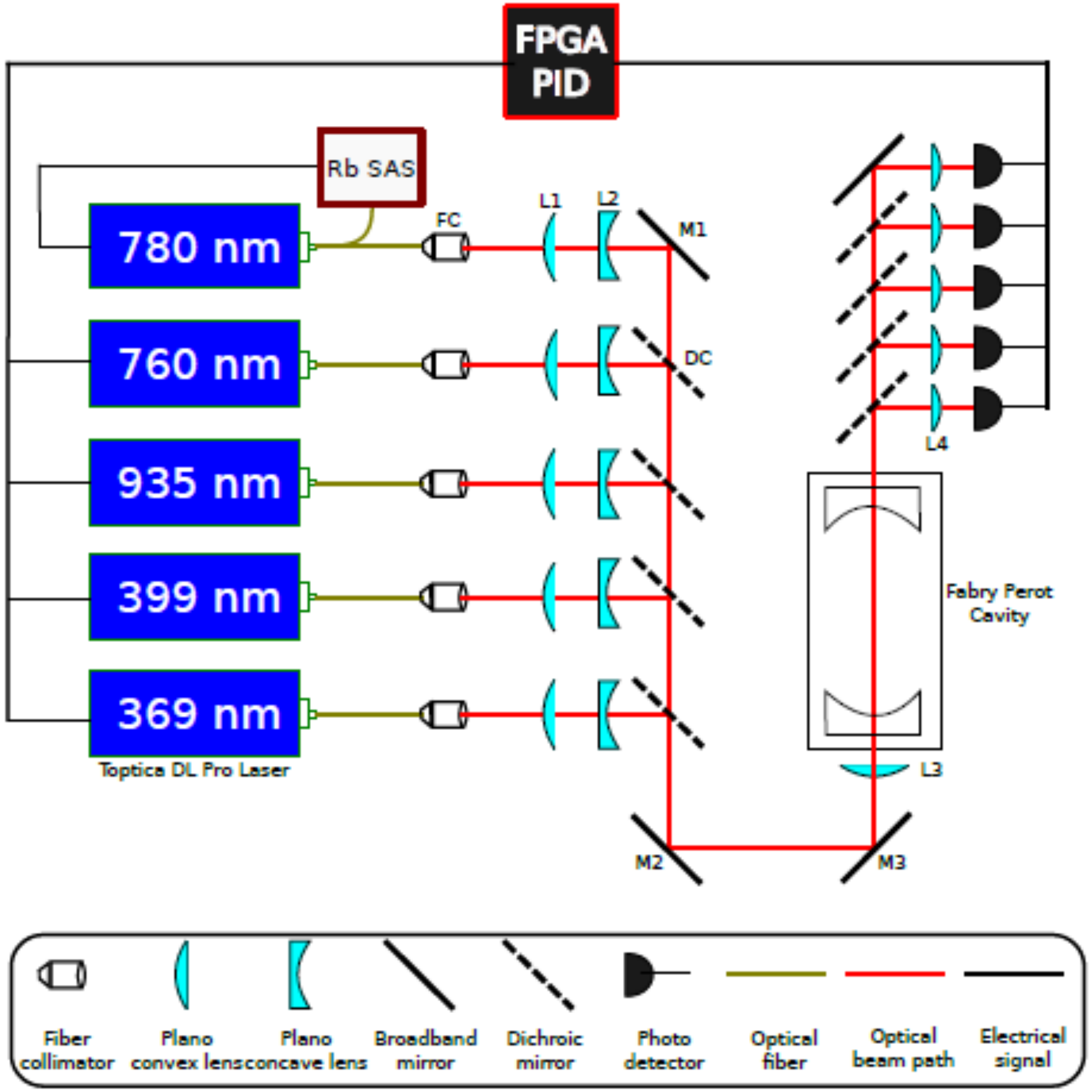
wavelength(nm)	f_{FC}(mm)	f_1 (mm)	$f_2(mm)$	Ld(mm)	f_3
369.0	4.02	150.0	-75.0	75.0	150.0
399.0	4.02	150.0	-75.0	75.0	150.0
760.0	8.00	125.0	-50.0	74.0	150.0
780.0	8.00	125.0	-50.0	74.0	150.0
935.0	8.00	150.0	-50.0	99.0	150.0

Cavity measurements



Lorentzian finesse ~ 400

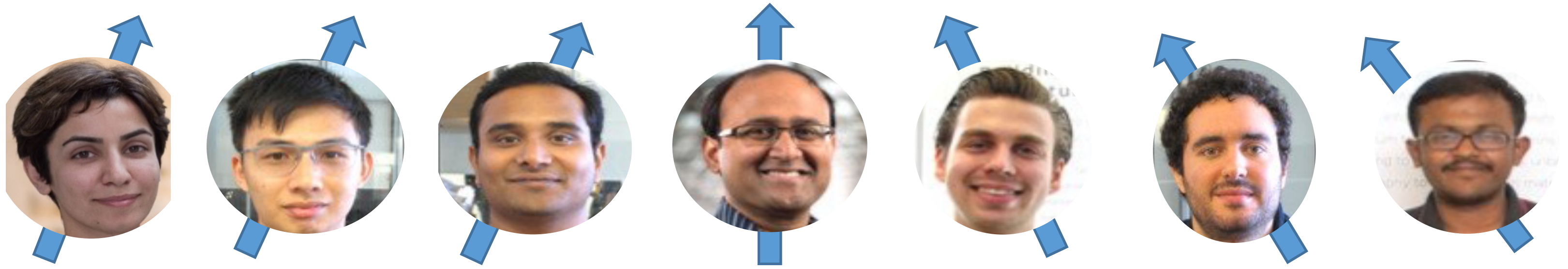
Single transfer cavity to lock multiple lasers



Summary and Outlook

- Alternate schemes for laser locking using a wavemeter and a transfer cavity
- Wavemeter lock has advantages of ease and scaling, but is limited by the resolution, accuracy and the sampling rate the instrument
- Cavity based lock has more resolution and sampling rate but cannot make absolute frequency measurements
- Combine both the schemes to obtain the advantages of both the systems.

References

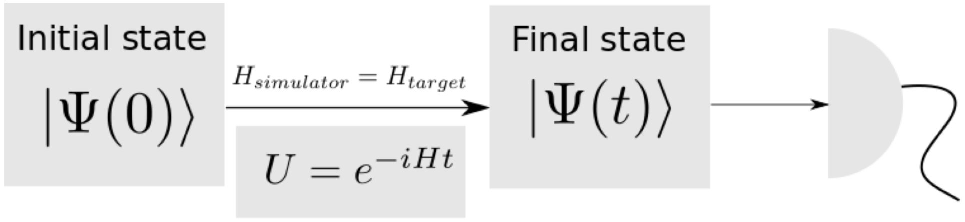


Fereshteh Gilbert Nikhil **Rajibul** Nikolay Roland Sainath

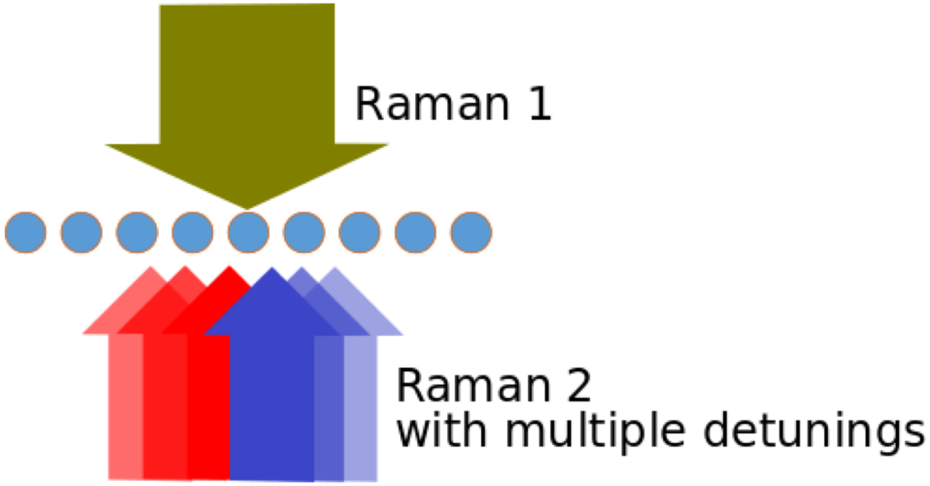
THANK YOU

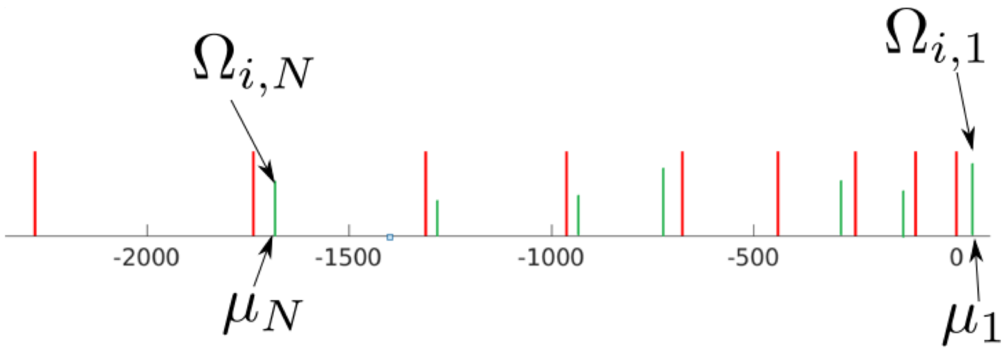
Extra slides

Analog Quantum Simulation



Multi frequency extension of
Mølmer-Sørensen scheme



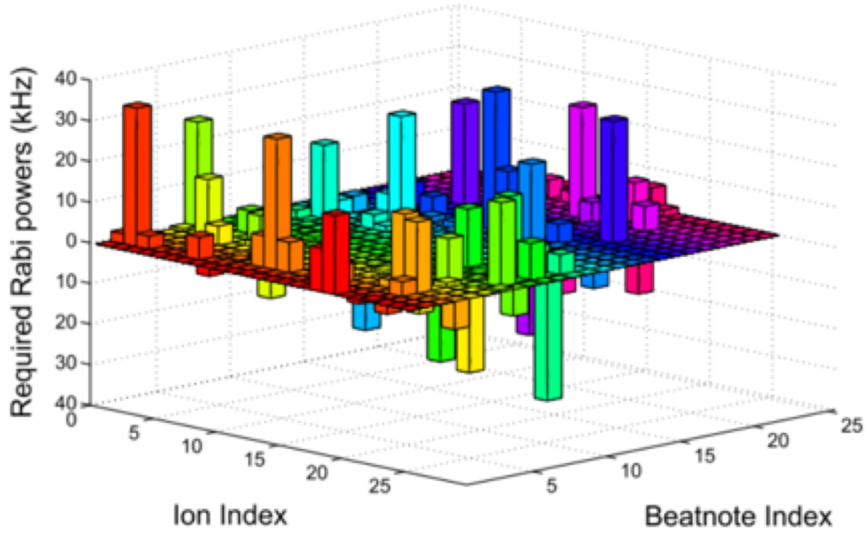


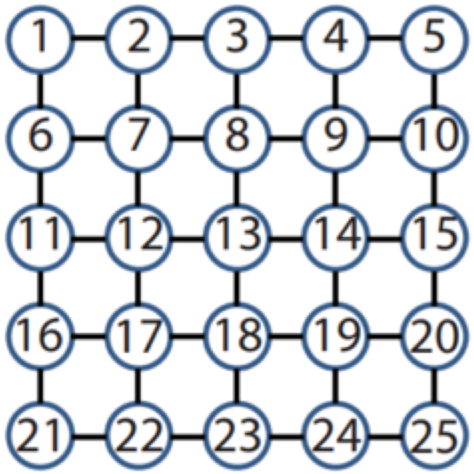
$$J_{i,j} = \sum_l \Omega_{i,l}\Omega_{j,l} \left(\frac{\hbar \Delta k^2}{2m}\right) \sum_k \frac{b_i^k b_j^k}{{\mu_l}^2 - \omega_k^2}$$

sum over various
Mølmer-Sørensen detunings

Optimize the values of $\{\mu_l, \Omega_{i,l}\}$ to create arbitrary J_{ij}

One such optimized solution to simulate 2D lattices*





Requires individual ion addressability with various Mølmer-Sørensen beams

*Korenblit, S., et al. NJP 14.9 (2012): 095024

Experimental parameters