1D Rydberg atom arrays: An entry point to studying isolated quantum many body systems out of equilibrium

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Quick Aside

Two ideas for this talk

1D Rydberg atom arrays quantum simulators

↓ Entry point

Studying isolated quantum systems out of equilibrium dynamics

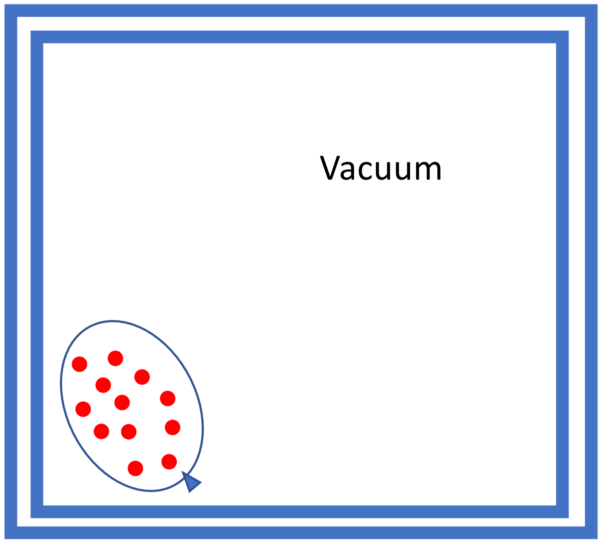
Entanglement entropy dynamics of system

↓ Behind

Characteristics of isolated quantum systems out of equilibrium

Motivation

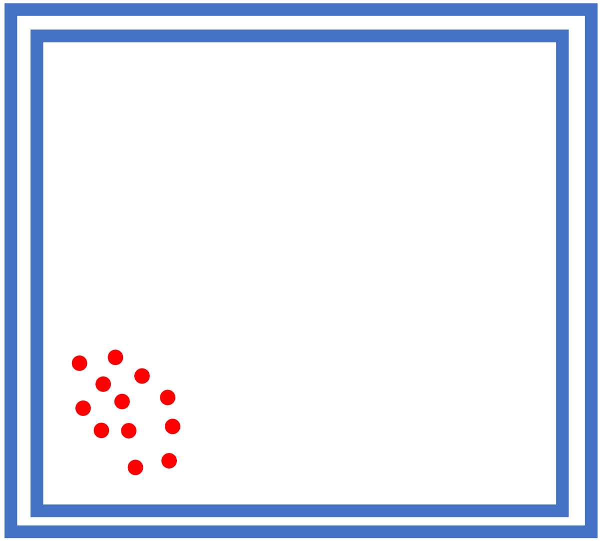
Classical Isolated System



- Adiabatic walls (no transfer of heat outwards)
- Balloon with ideal gas inside
- Rest of the chamber is a vacuum

Motivation

Classical Isolated System

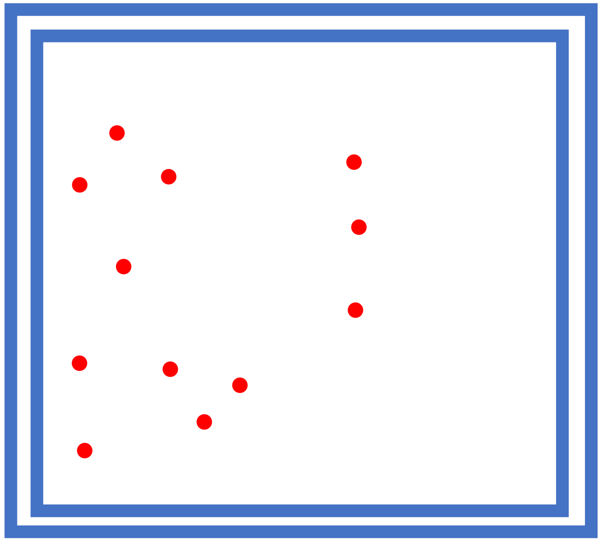


Out of equilibrium initial state

- Adiabatic walls (no transfer of heat outwards)
- Balloon with ideal gas inside
- Rest of the chamber is a vacuum
- **Peirce the balloon**

Motivation

Classical Isolated System

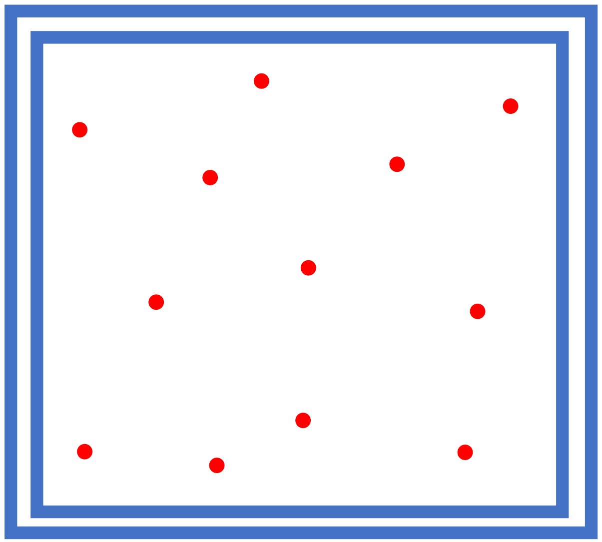


Out of equilibrium state

- Adiabatic walls (no transfer of heat outwards)
- Balloon with ideal gas inside
- Rest of the chamber is a vacuum
- **Peirce the balloon**
- **Air particles spread**

Motivation

Classical Isolated System



Reaches Equilibrium

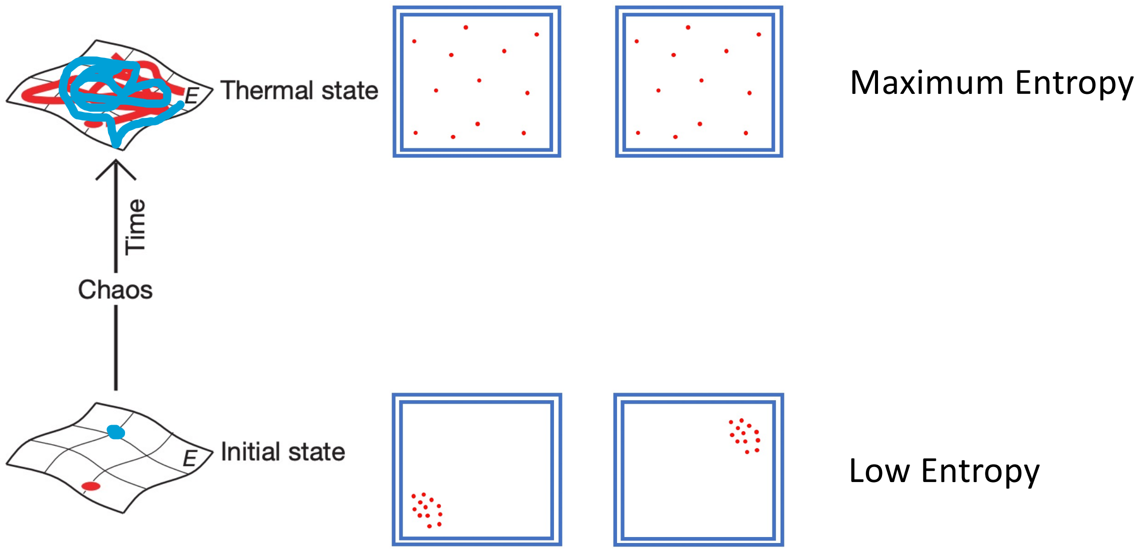
- Adiabatic walls (no transfer of heat outwards)
- Balloon has N particles with total energy E
- Rest of the chamber is a vacuum
- **Peirce the balloon**
- **Air particles spread**
- **System thermalizes**

Macroscopic observables reach steady average value:

$$\langle O(t) \rangle \longrightarrow \langle O \rangle_{thermal}$$

Motivation

Statistical Physics



What happens in an isolated quantum system?

- Unitary time evolution

$$|\varphi(t)\rangle = \mathrm{U(t)}|\varphi(0)\rangle$$

- Can the system thermalize in the same way?
- Can we associate entropy in the same way?
- Are there global properties that can help us understand this?

Rigol, et al. *Nature* 452, 854–858 (2008)

Contents

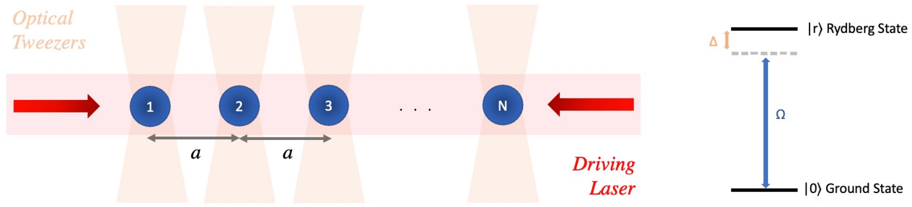
1. Introduce the model
   - Rydberg Atoms
   - Rydberg Blockade
   - Ising Type Hamiltonian

2. Generating order phases

3. Bringing the system out of equilibrium

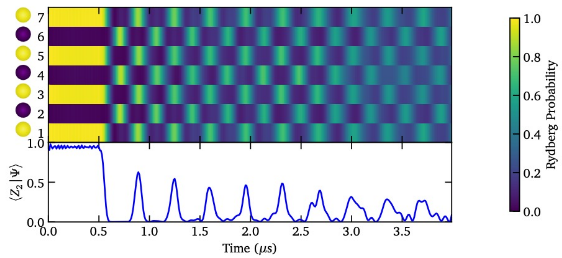
4. Why is it a good entry point?

1.



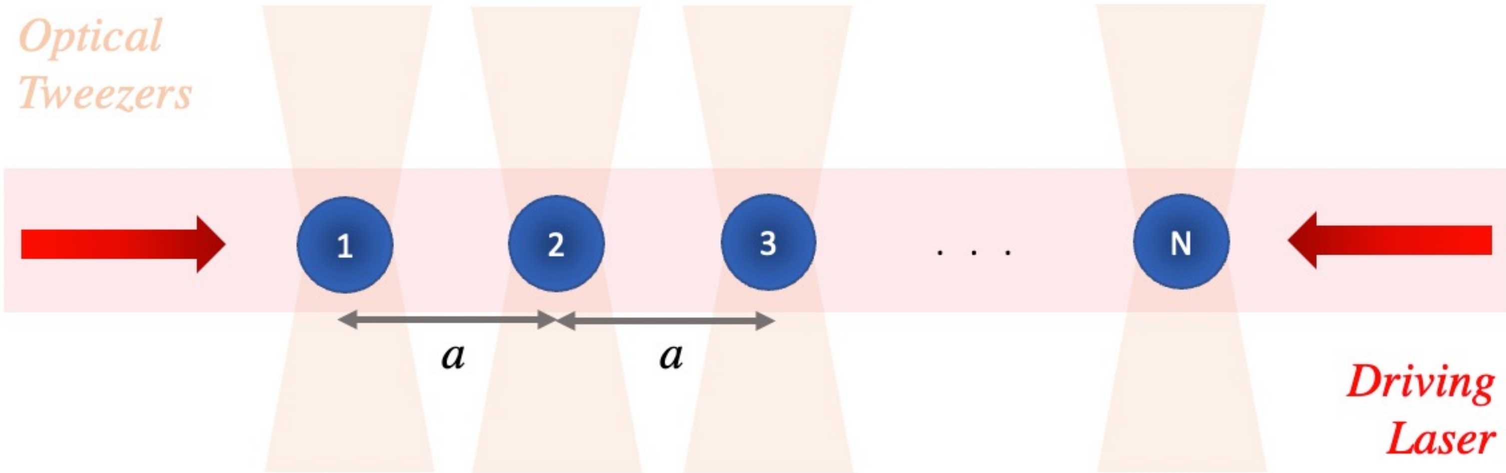
2.

3.



Running numerical simulations of quantum simulation protocols done on ultra cold neutral atoms

Set up



$$\frac{H}{\hbar} = \frac{\Omega(t)}{2} \sum_i^N \sigma_i^x - \Delta(t) \sum_i^N n_i + \sum_{i<k}^N V_{ik}\, n_i n_k$$

i = atom site

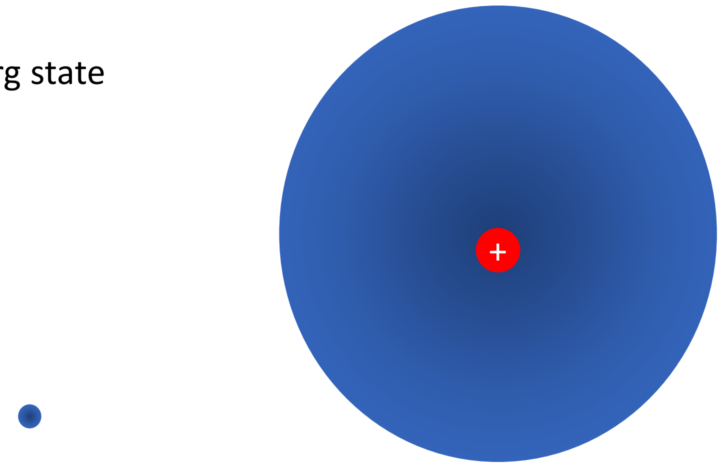
Driving term

Detuning term

Interaction term

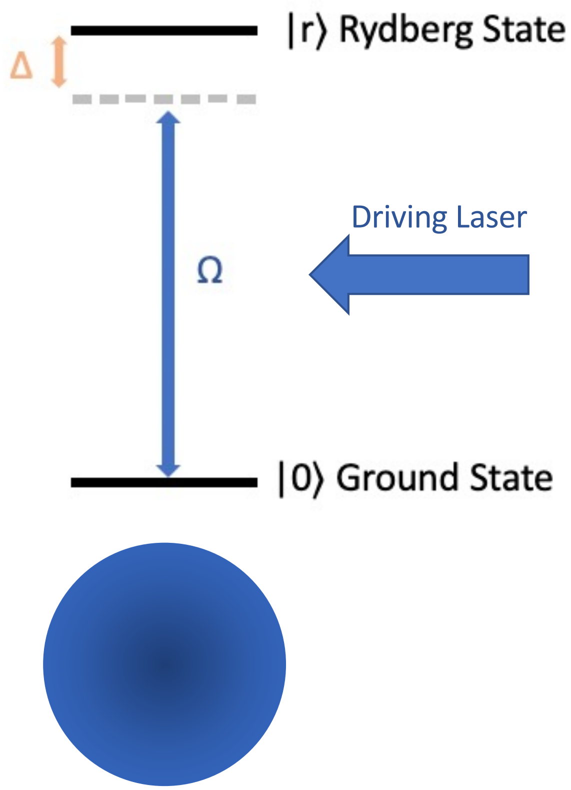
Rydberg Atoms: What are they?

- Single electron in a highly excited state (n ~ 40 - 100)
- Appears Hydrogen-like
- 'Giant Atoms'
- Large dipole moment
- Strong van der interactions
- Highly excited state is called the Rydberg state



Size $\sim 0.2\ nm$ $>\ 200\ nm$

Rydberg Atoms: Encoding as qubit

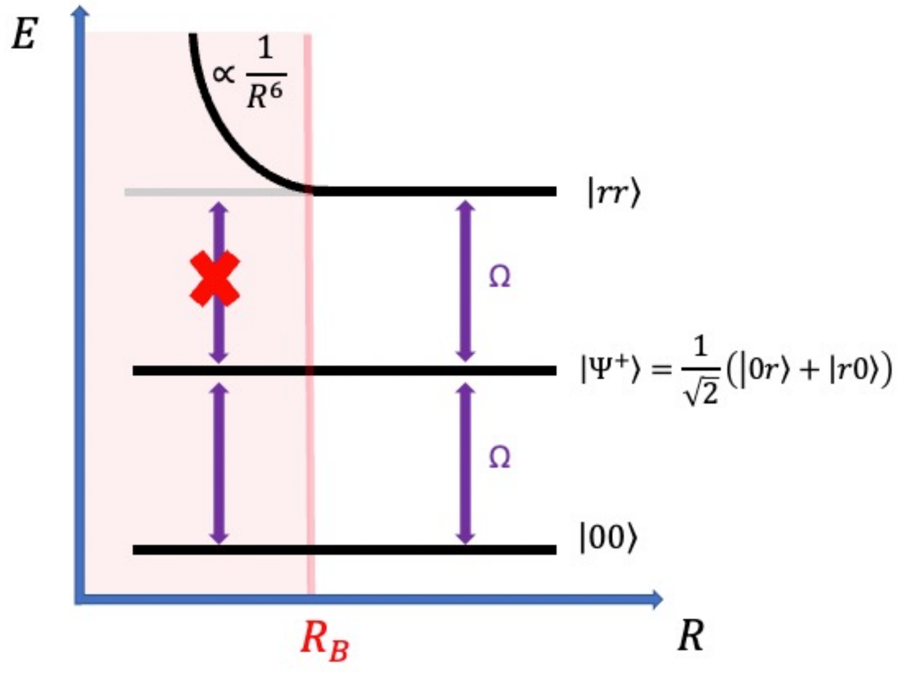


- Use a laser to couple Ground and Rydberg states of atom
- Two level system forms our qubit

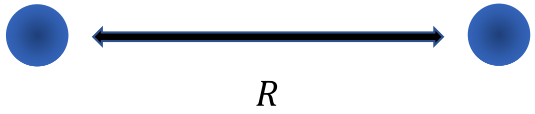
$\frac{\Omega}{2\pi}$ - Rabi Frequency (MHz) Strength of coupling between states

$\frac{\Delta}{2\pi}$ - Detuning (MHz) How far of resonance driving laser is

Interaction and Rydberg Blockade



Two atoms



- Strong **van der Waals interaction** between Rydberg atoms $\propto 1/R^6$
- This results in energy shift of $|rr\rangle$ state
- The blockade radius R_B – characteristic radius where this starts to take effect
- Shared excitation amongst atoms result in entangled states

Many Body Hamiltonian

Evolve the system with Trotter-Suzuki decomposition:

$$|\Psi(t)\rangle = \prod_{i=1}^{N} e^{-iH[\Omega,\ \Delta(t_i)]dt_i}\,|\Psi(t=0)\rangle$$

$dt_i = 0.01\ \mu s$

$$\frac{H}{\hbar} = \frac{\Omega(t)}{2}\sum_i^N \sigma_i^x \; - \; \Delta(t)\sum_i^N n_i \; + \; \sum_{i<k}^N V_{ik}\, n_i n_k$$

i = atom site

Driving term

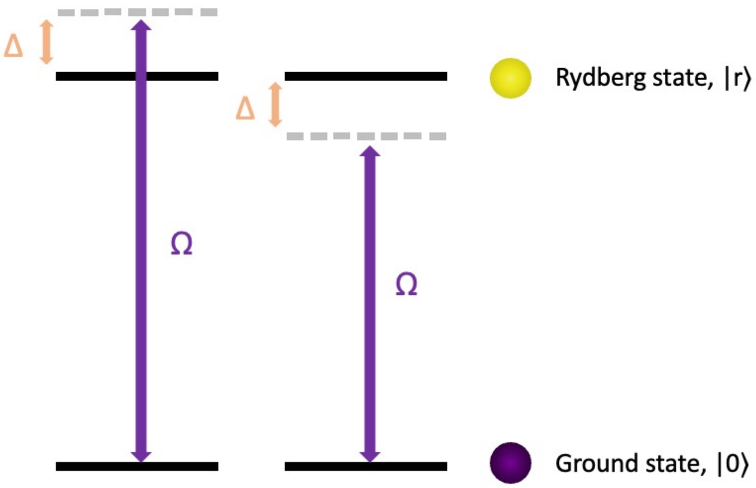
Detuning term

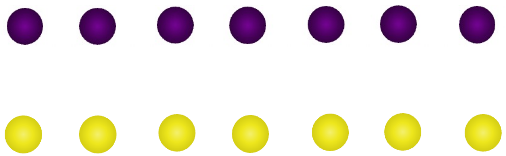
Interaction term

$\Omega(t)/2\pi = \Omega_0/2\pi = 4.00$ (MHz)

Bernien, et al *Nature* 551, 579-584 (2017)

Using blockade to generate ordered states

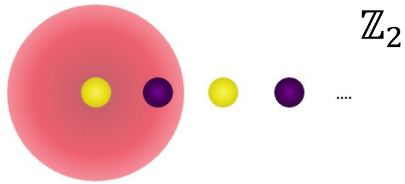




Ground state $\Delta \ll 0$

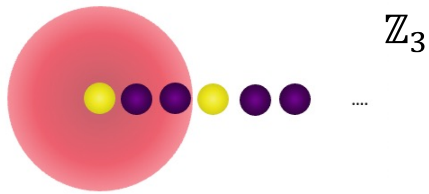
Ground state $\Delta \gg 0$

But Rydberg Blockade constraint…. **So for $\Delta \gg 0$**



NN Blockade

$V_{i,i+1} > \Delta \gg V_{i,i+2}$



NNN Blockade

$V_{i,i+1} \gg V_{i,i+2} > \Delta \gg V_{i,i+3}$

Note:

- Focus NN Blockade
- Odd number of sites (No degeneracy in our $\Delta \gg 0$ ground states)

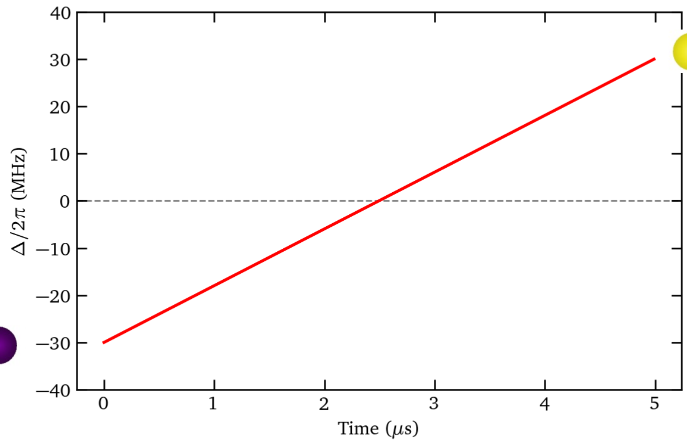
Using blockade to generate ordered states

Evolve the system adiabatically

By adjusting the separation between atoms a, we can sweep through detuning values to generate desired ordered states:

Focus on 7 Atoms

$\Delta \ll 0$ Ground state



$\Delta \gg 0$ Ground State

$\mathbb{Z}_2$

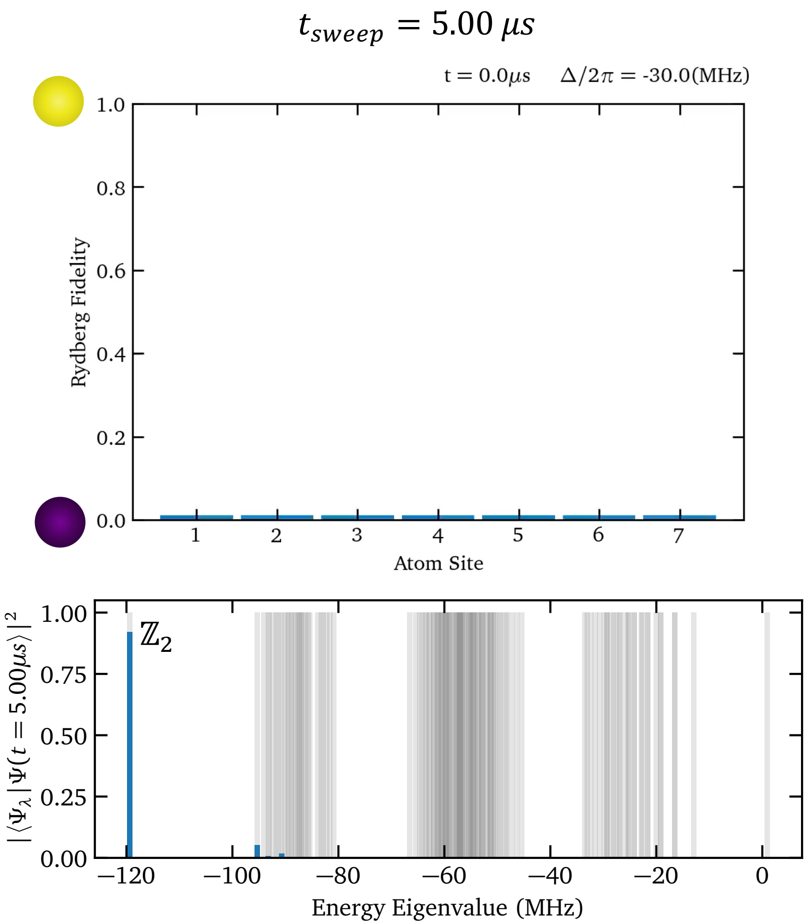
Note
- Fo
- O

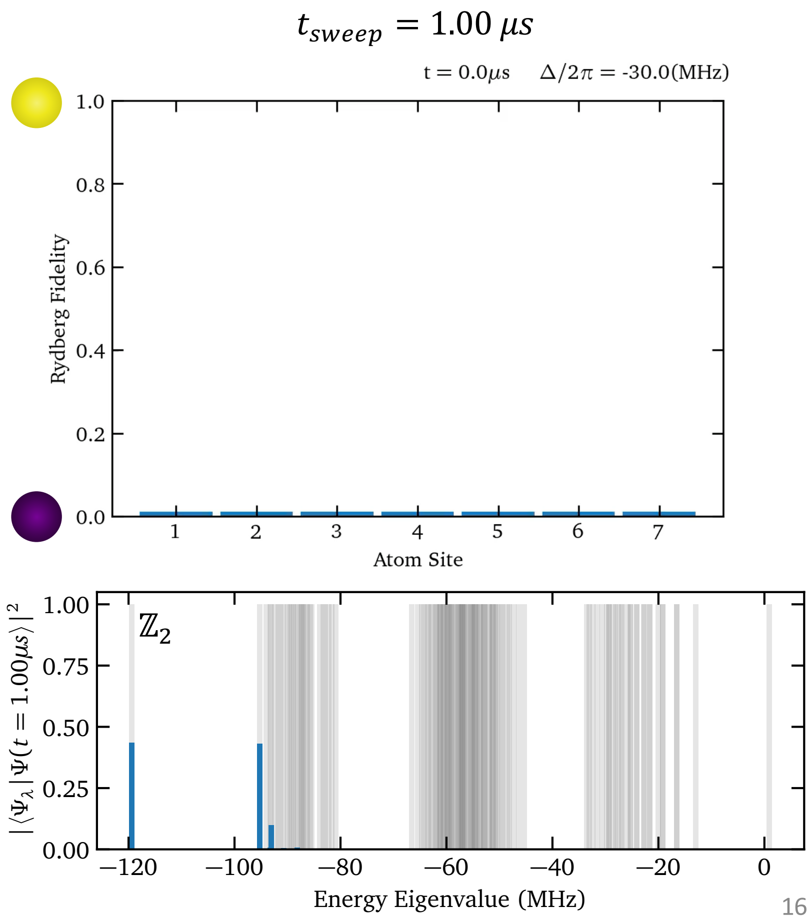
$\Delta \gg 0$

Odd GS

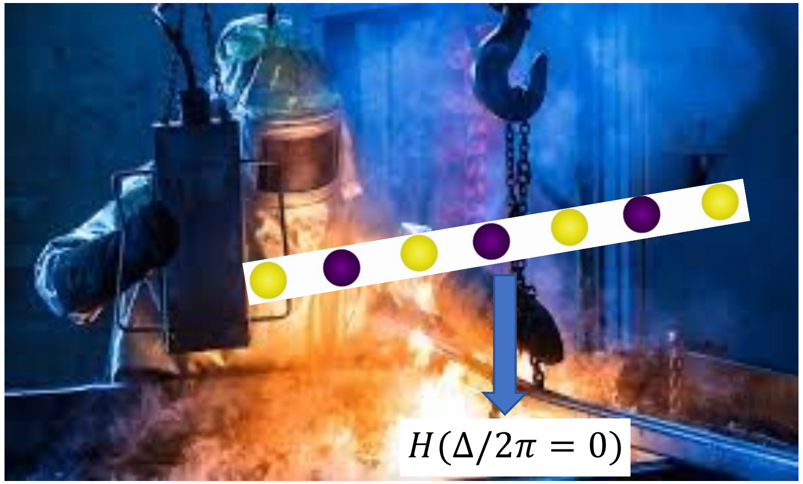
Even GS

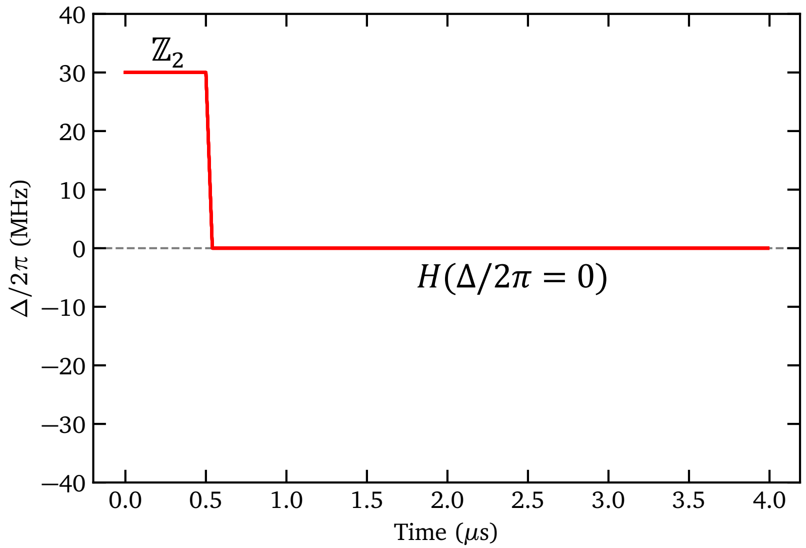
Using blockade to generate ordered states



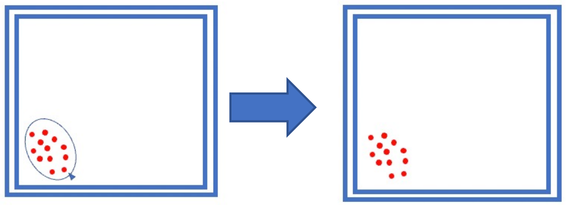


What if we intend on going quickly: quenches

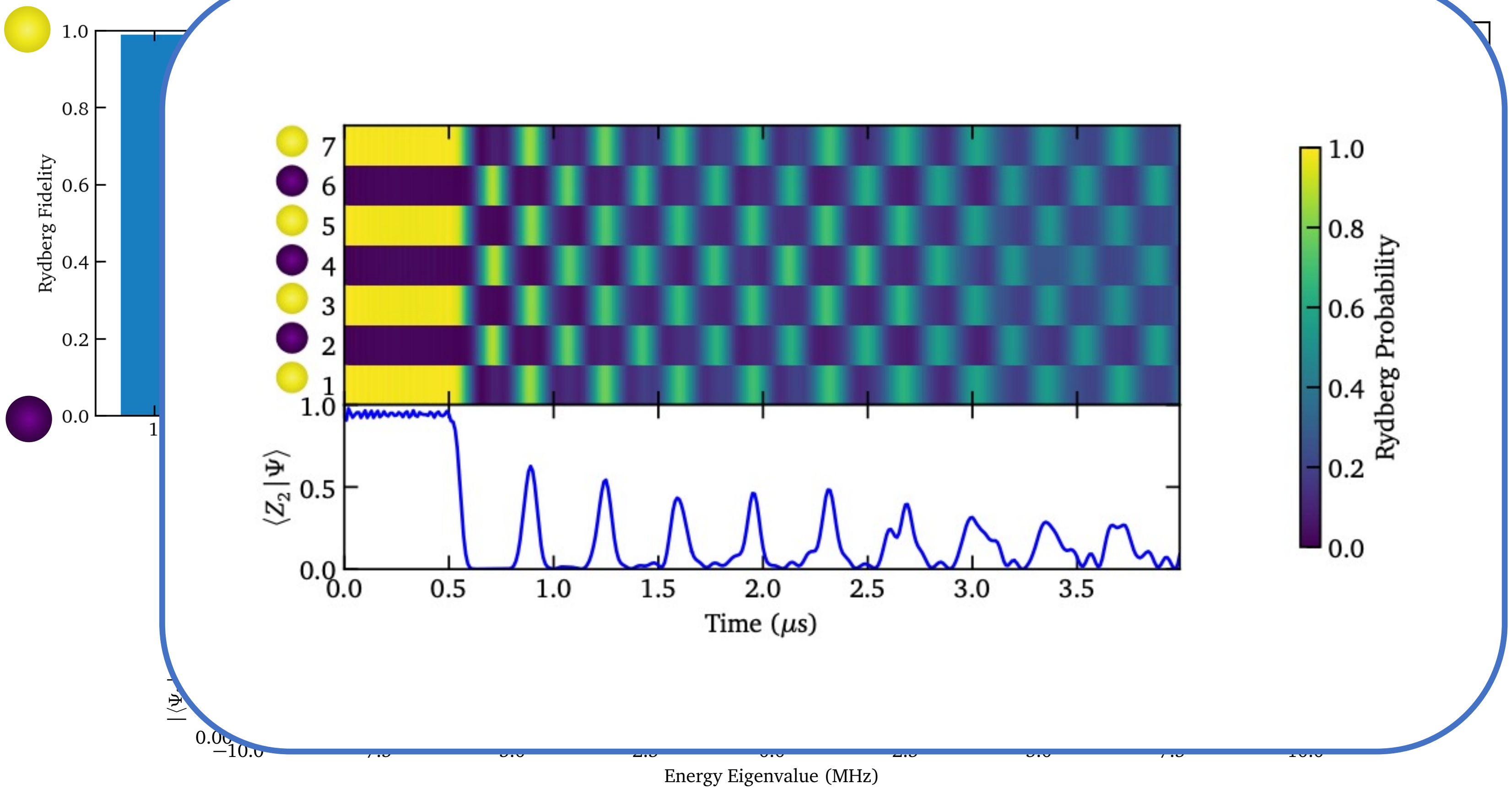




- How we take the system out of equilibrium
- Analogues to balloon popping



Taking the system out of equilibrium



So why is this a good entry point?

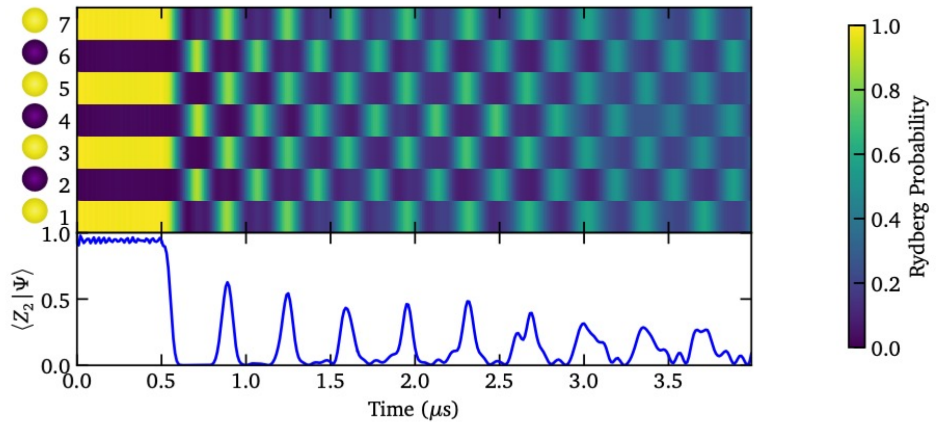
1. Interesting novel behavior
   - Quantum many body scars

2. Tunability and versality to try different things
   - Local quenches
   - Slower quenches
   - Different initial configurations

3. What lies underneath
   - Entanglement
   - Propagation of information

So why is this a good entry point?

1. Interesting novel behavior



- Revival of the initial state after the quench is a behavior know as **quantum many body scars**
- Type of behavior know as **weak ergodicity breaking**

$$|\varphi(t)\rangle = \sum_n a_n e^{-iE_n t} |n\rangle$$

Quantum Chaotic System ('thermalizes')

Quantum many body scars

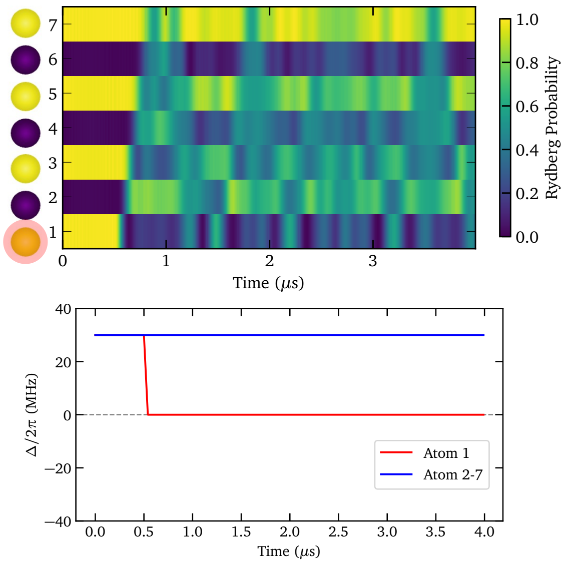
Many Body Localization (does not 'thermalize')

Serbyn, Maksym, et al. *Nature Physics* 14, 745-749 (2018)

So why is this a good entry point?

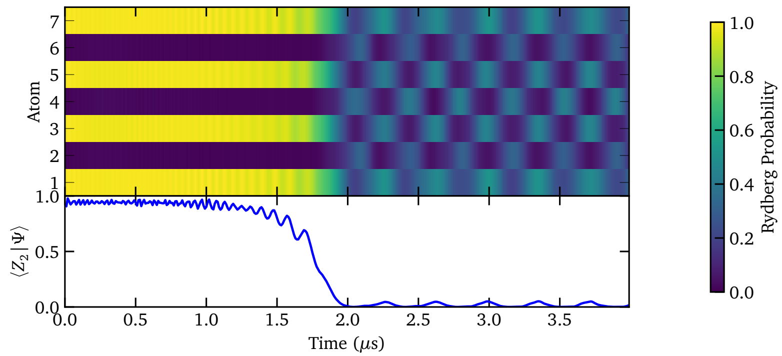
2. Tunability and versatility to try different things

Local addressing and quenches



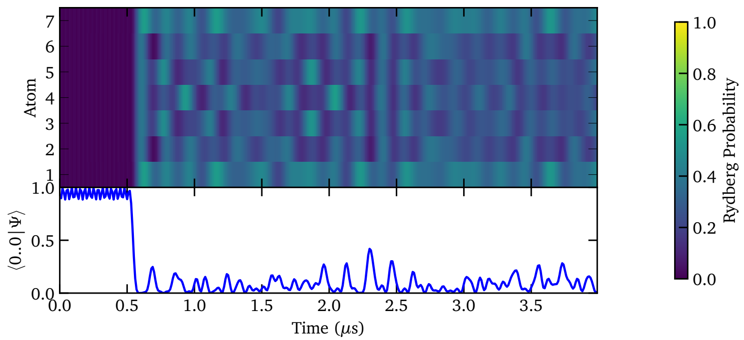
- Propagation of information
- Formations of correlations

Vary the speed to the quench



- Evaluate different out of equilibrium regimes

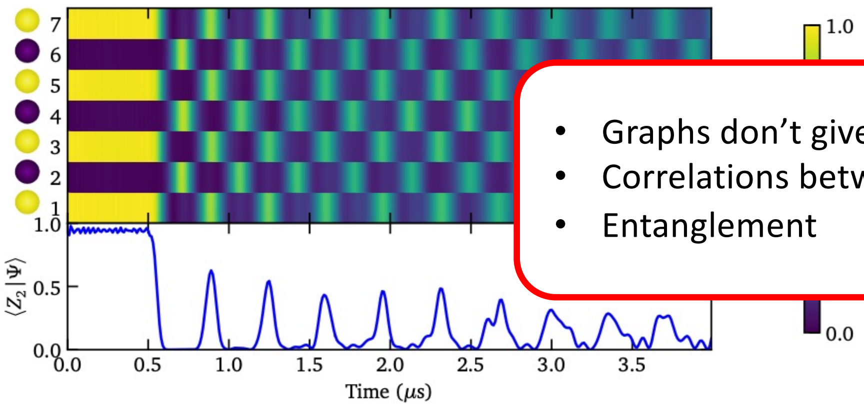
Quench different initial states



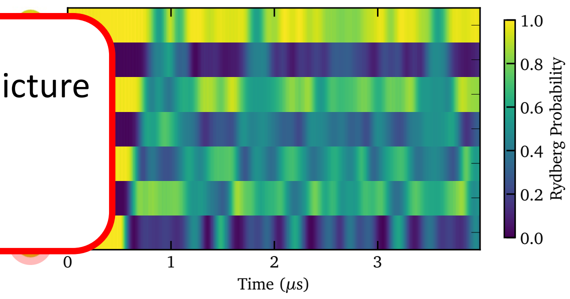
- Investigate which states have scar behavior

So why is this a good entry point?

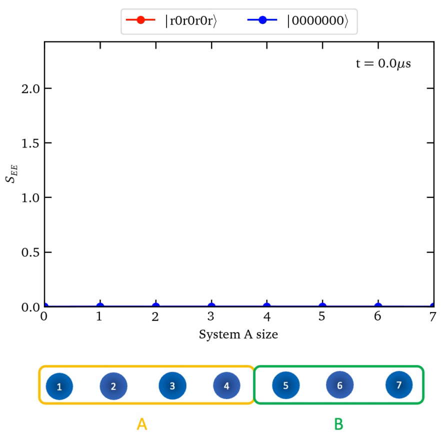
- What lies underneath

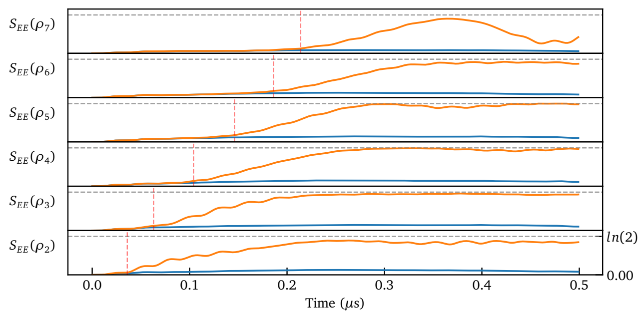


- Graphs don't give the whole picture
- Correlations between atoms
- Entanglement



Looking at entanglement growth and scaling with the system





Acknowledgements

- Supervisor: Prof Stuart Adams
- PHD Student: Toonyawat Angkhanawin

Values

$$\frac{H}{\hbar} = \frac{\Omega}{2} \sum_i^N \sigma_i^x - \Delta \sum_i^N n_i + \sum_{i<k}^N V_{ik}\, n_i n_k$$

i = atom site

Driving term

Detuning term

Interaction term

$$\sigma_i^x = |0_i\rangle\langle r_i| + |r_i\rangle\langle 0_i|$$

$$n_i = |r_i\rangle\langle r_i|$$

$$V_{ik} = \frac{C_6}{r^6}$$

$\Omega/2\pi$ = 4.00 (MHz)

$$r = a|i-k|$$

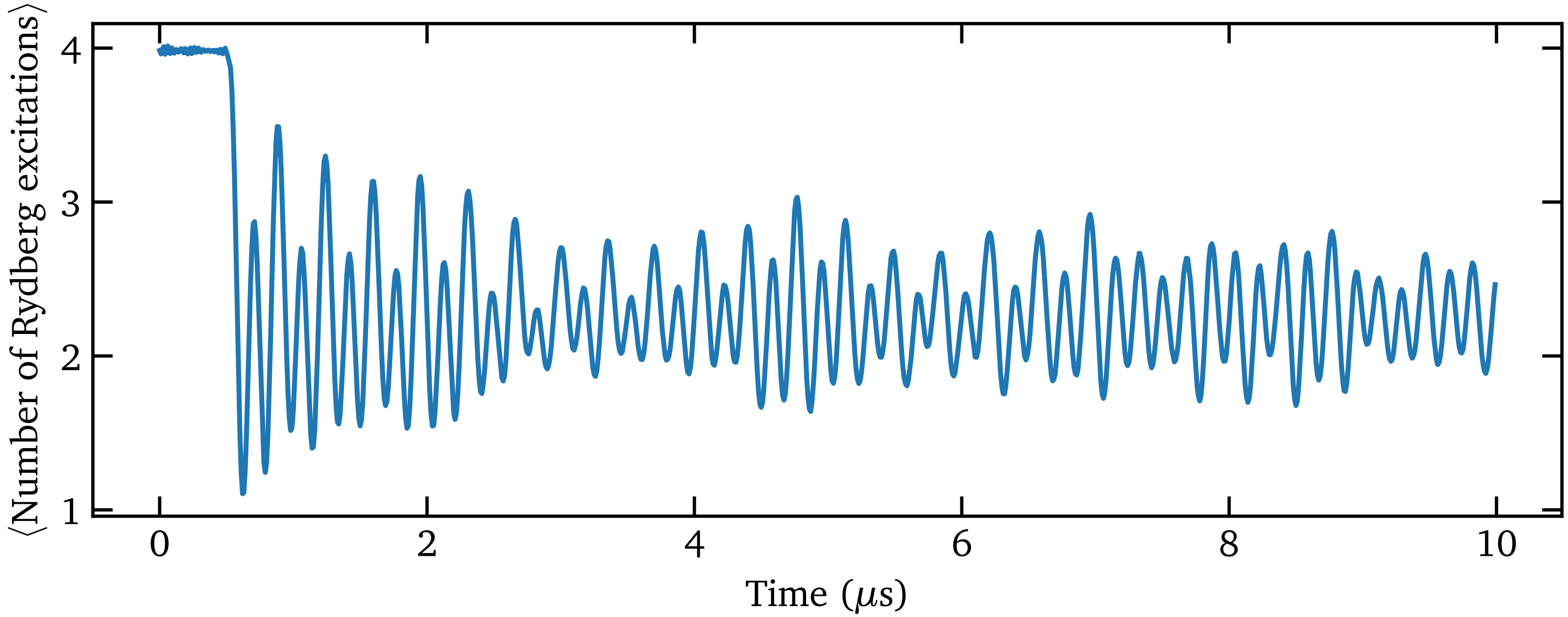
Rb Atoms: $C_6/ 2\pi$ = 863000 MHz μm^6

Evolve the system with Trotter-Suzuki decomposition:

$$|\Psi(t)\rangle = \prod_{i=1}^{N} e^{-iH[\Omega,\ \Delta(t_i)]dt_i}\, |\Psi(t=0)\rangle \qquad dt_i = t_i - t_{i-1} \qquad dt_i = 0.01\ \mu s$$

Bernien, et al *Nature* 551.7682 (2017)

Thermalization or lack there of



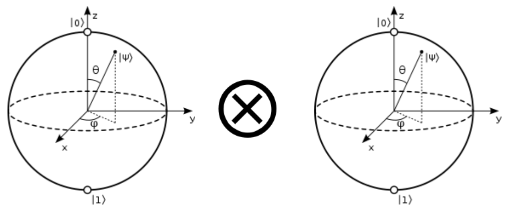
Entanglement: can this offer us any further insight?

Two qubits

Product states

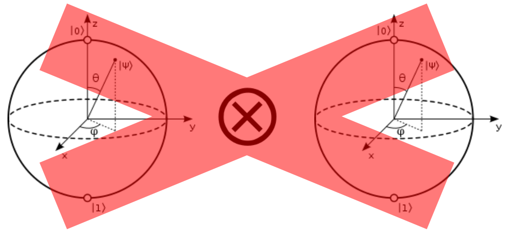
$$\frac{1}{\sqrt{2}}\big(|0\rangle + |r\rangle\big) \otimes \frac{1}{\sqrt{2}}\big(|0\rangle + |r\rangle\big)$$

Atom 1 Atom 2



Entangled states

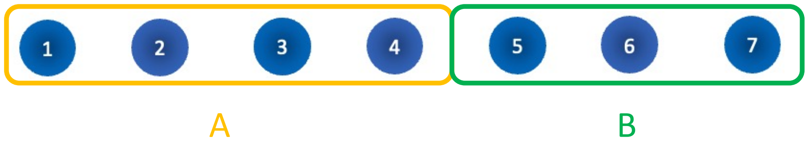
$$|\Psi^{+}\rangle = \frac{1}{\sqrt{2}}\big(|0r\rangle + |r0\rangle\big)$$



Need Atom 2 to fully describe the state of atom 1

Entanglement Entropy

$|\varphi\rangle$ Density Matrix $\rho = |\varphi\rangle\langle\varphi|$



$$|\varphi\rangle = |\varphi\rangle_A \otimes |\varphi\rangle_B$$

$$|\varphi\rangle \neq |\varphi\rangle_A \otimes |\varphi\rangle_B$$

Reduced Density Matrix

$\rho_A = Tr_B(\rho)$ Everything we can know about A without B

$$n_i = |r_i\rangle\langle r_i|$$

Von Neuman Entropy Between A and B

How uncertain is the information in ρ_A