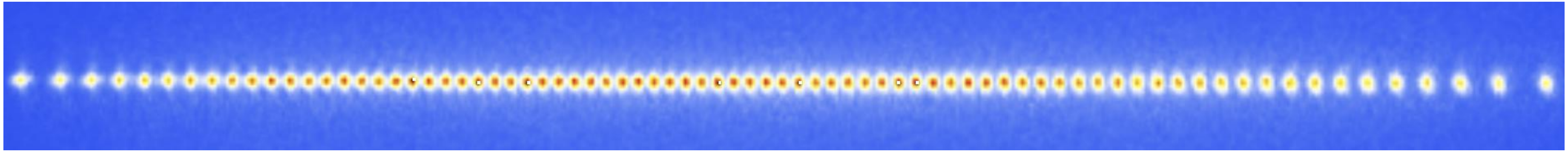
# Towards Trapped-Ion Analog Simulation of Lattice Gauge Theories



RICE

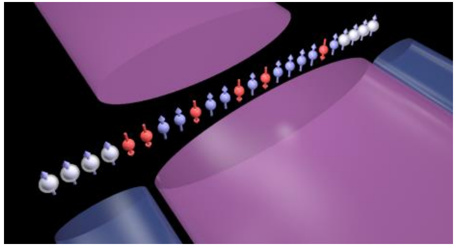
GHP Workshop 2023

Guido Pagano

14th April 2023

# Outline

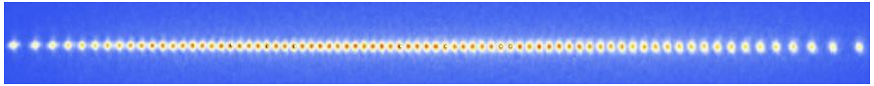
## Introduction:



- Trapped-Ion Quantum systems

## Trapped-Ion Quantum Simulation of LGTs

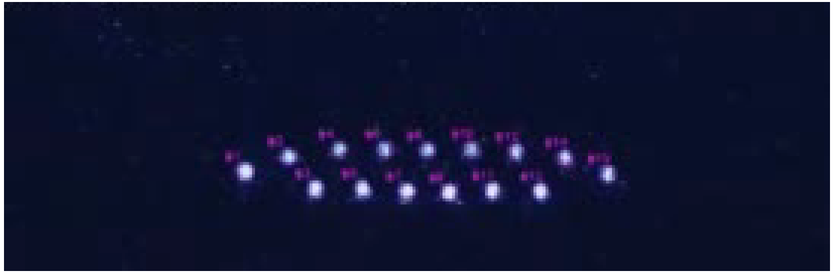
- Digital realizations of Schwinger model (2016, 2022)
- Analog route: Three-spin interactions, B. Andrade et al., QST 7 034001, (2022)
- Hybrid Analog-Digital simulations, Z. Davoudi et al., PRR 7 034001, (2022)

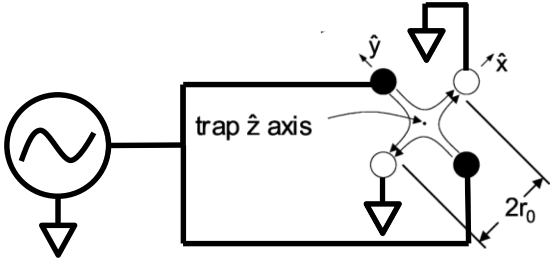


## Outlook and Perspectives

- Experimental progress at Rice University

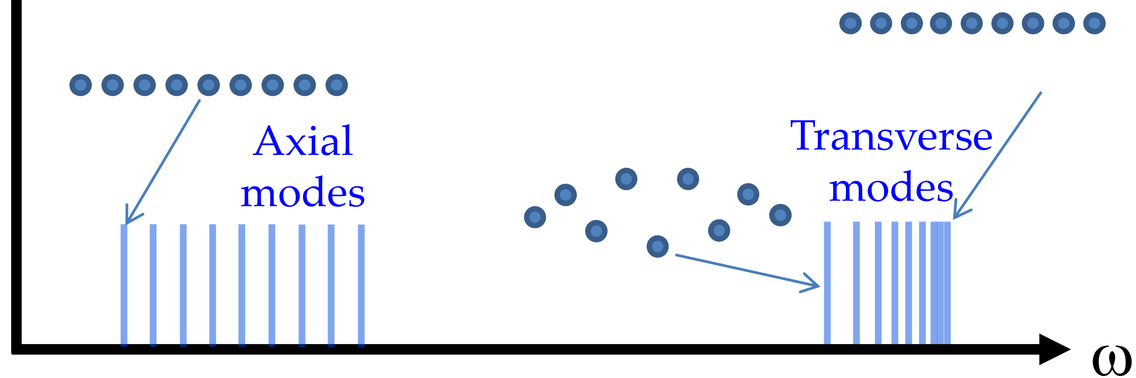
# Self-organized Ion crystals






$$H_M = \frac{\hat{p}^2}{2m} + \frac{m}{2}\omega_\alpha^2 x_{\alpha i}^2 + \frac{q^2}{8\pi\epsilon_0}\frac{1}{|r_i - r_j|}$$

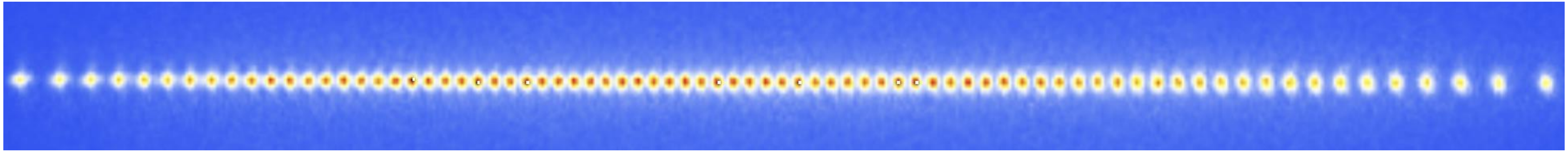
N ions ⟷ 3N normal modes





Mechanical Paul trap, https://www.youtube.com/watch?v=pG1TcnpsY_8

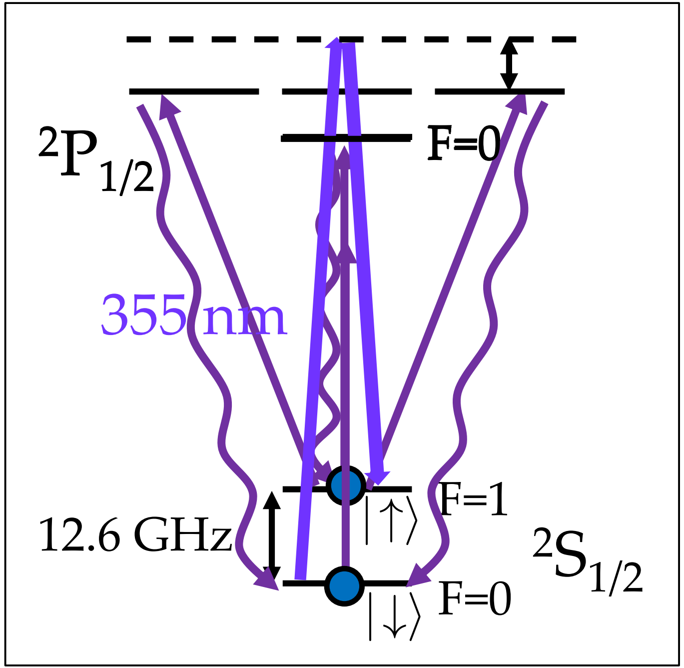
# A many-body system assembled atom by atom



## $^{171}Yb^{+}$ Clock states qubit

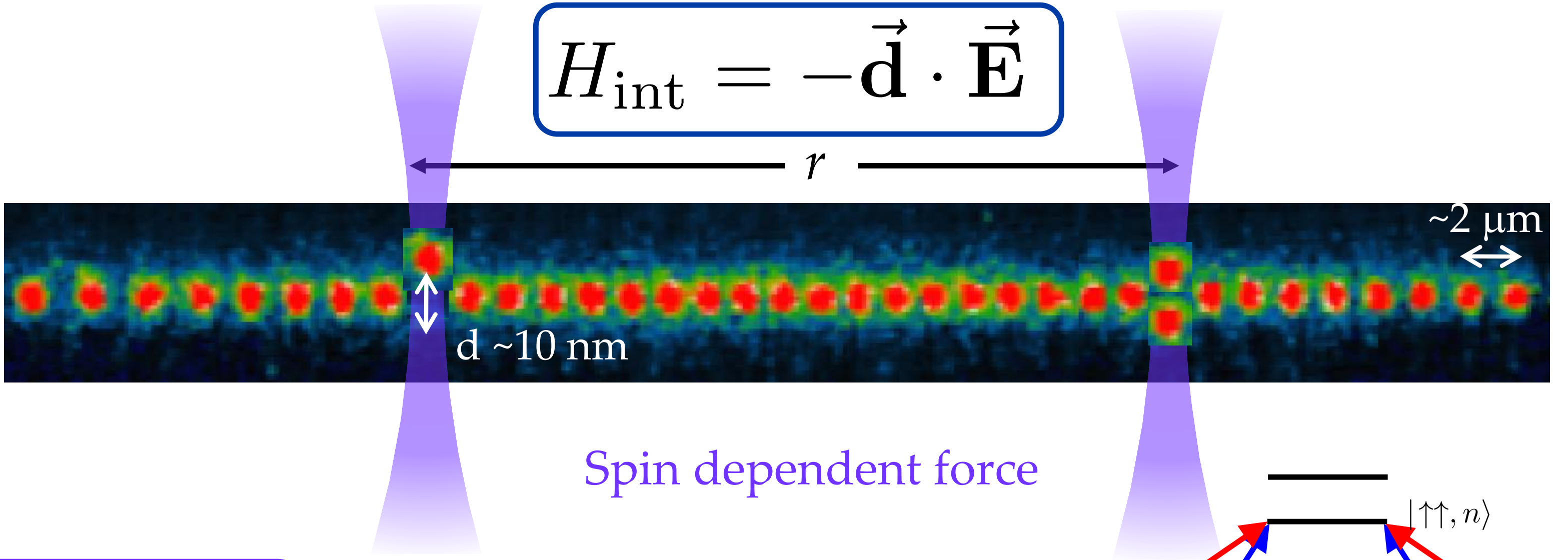
- Coherence time: $T_2$>10 minutes [1]
- High fidelity state preparation: > 99.9% in ~ 10 μs
- High speed readout: > 99.9% in ~ 100 μs
- High Fidelity one (>99% in 1 μs) and two qubit gates (~99% in 500 μs)

[1] P. Wang et al., Nat. Comm. **12**, 233 (2021)



# Wiring Trapped-ion Qubits with Laser beams

$$H_{\text{int}} = -\vec{\mathbf{d}} \cdot \vec{\mathbf{E}}$$




Spin dependent force

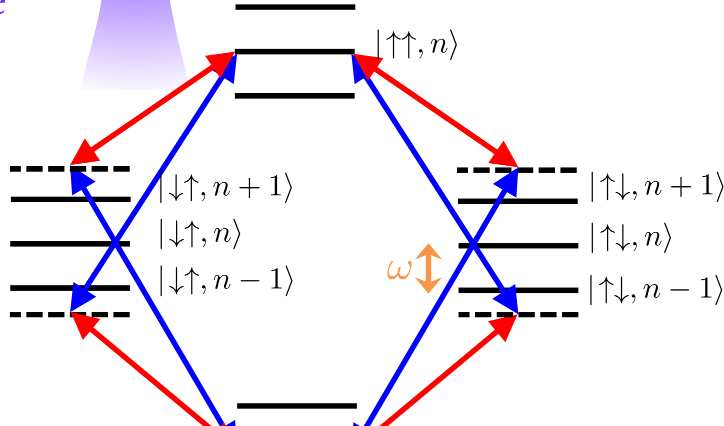
$$|\downarrow\rangle|\downarrow\rangle \longrightarrow |\downarrow\rangle|\downarrow\rangle$$
$$|\uparrow\rangle|\uparrow\rangle \longrightarrow |\uparrow\rangle|\uparrow\rangle$$

$$\Delta E = \frac{e^2}{\sqrt{\delta^2 + r^2}} - \frac{e^2}{r} \sim \frac{(e\delta)^2}{2r^3}$$

$$|\downarrow\rangle|\uparrow\rangle \longrightarrow e^{i\varphi}|\downarrow\rangle|\uparrow\rangle$$
$$|\uparrow\rangle|\downarrow\rangle \longrightarrow e^{i\varphi}|\uparrow\rangle|\downarrow\rangle$$

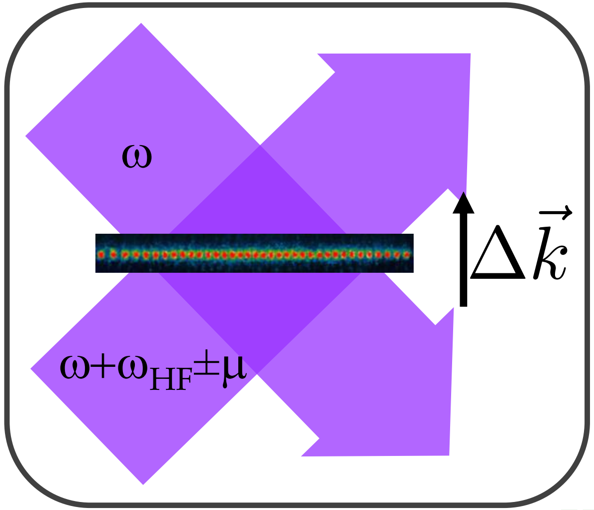
$$\varphi = \frac{\Delta E\, t}{\hbar}$$

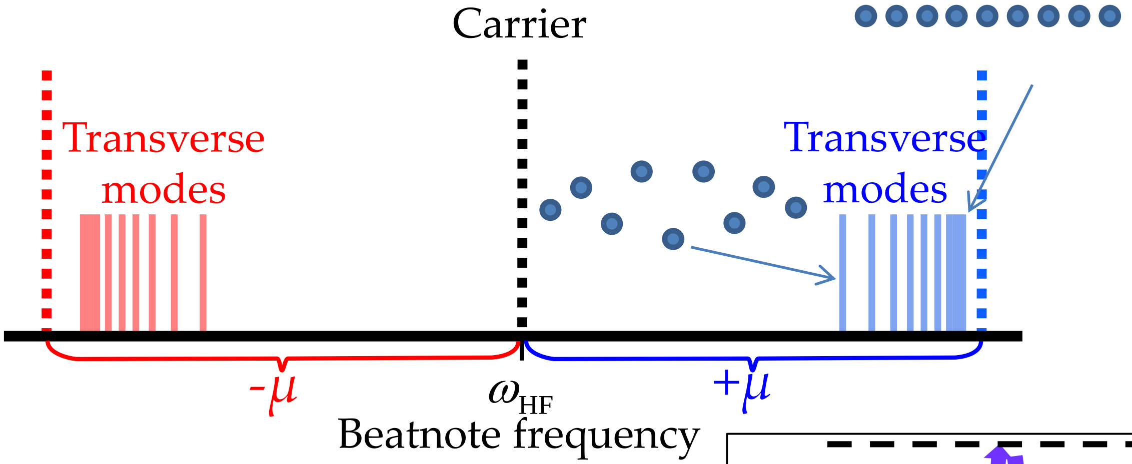
Cirac & Zoller (1995)
Molmer & Sorensen (1999)
Solano, et al. (1999)
Milburn, et al. (2000)




$$H_{\text{eff}} \sim \sigma_i^x \sigma_j^x$$

# Generating Spin Hamiltonians

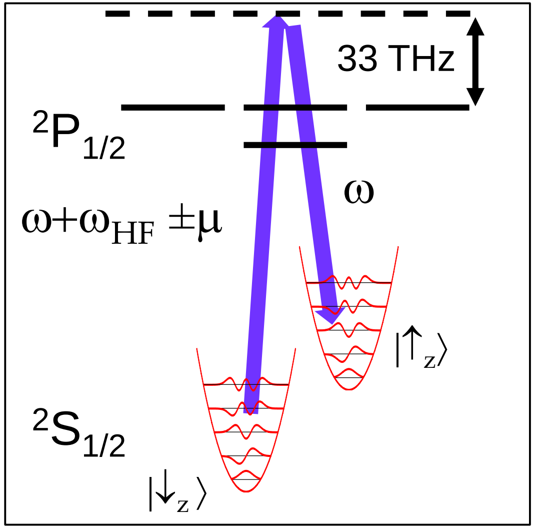



$$H_{eff} = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + \sum_{i,\alpha} B_\alpha \sigma_i^\alpha$$

$$\frac{J_0}{|i-j|^\alpha}$$

$0.5 < a < 2$



# Non-Equilibrium Studies with Trapped Ions

## Long-Range Transverse Field Ising Model

- ➢ Breaks Integrability
- ➢ Theoretically Challenging
- ➢ Model for quantum systems in nature

$$H_{\text{eff}} = \sum_{ij} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

$$J_{ij} \sim \frac{J_0}{|i-j|^\alpha}$$

Reviews:

- C. Monroe, *et al.*, RMP **93** 025001 (2021)
- N. Defenu, *et al.*, RMP in press (2023)

## Quantum quenches and Thermalization in Spin LR Systems

Many-Body Localization [1,2]

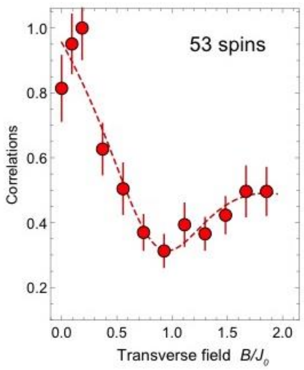
[1] Smith *et al.*, (Nature Phys. 2016)
[2] Bridges *et al.*, (Science 2019)

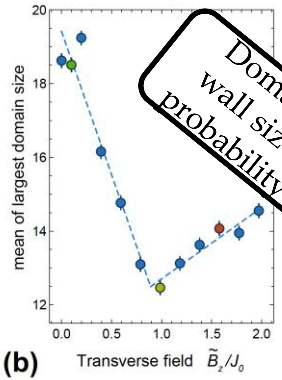
Dynamical Phase transition [3,4]

[3] Zhang, GP, *et al.*, Nature (2017)
[4] Jurcevic, *et al.*, PRL (2017)

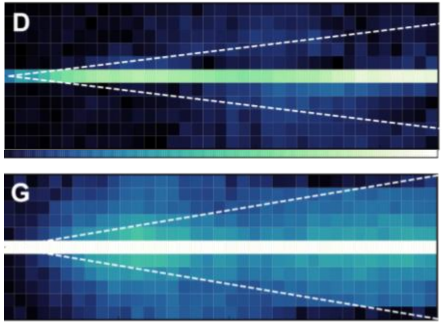
Confinement of Domain Walls [5]

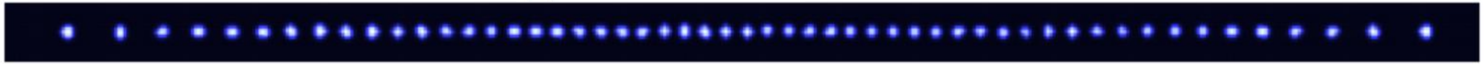
[5] Tan, Becker, *et al.*, Nature Phys. (2021)



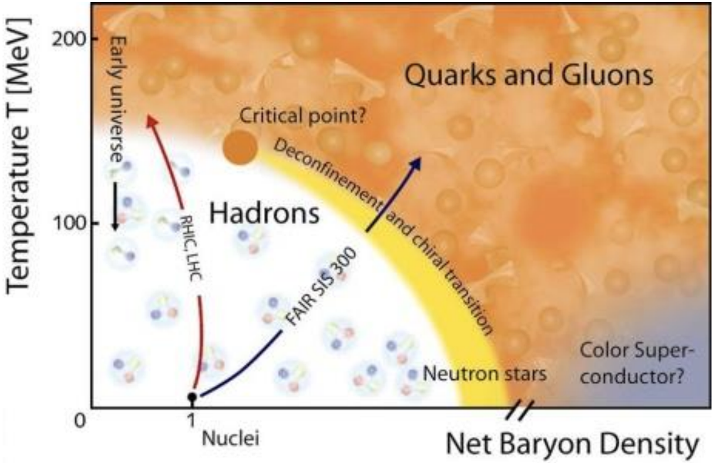




Domain wall size probability



# From Spin models to NP and HEP models




Solving QCD on a lattice:

- Phase diagram largely unexplored
- MonteCarlo has sign problem

Roadblock for both Real-time dynamics and equilibrium calculations

$$\mathcal{L}(\psi, F^{\mu\nu}, ...) \longrightarrow H(\sigma_i^x, a^\dagger, \ldots)$$

# From Spin models to NP and HEP models

$$\mathcal{L} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Kogut – Susskind staggered fermions
+
Jordan-Wigner Transformation

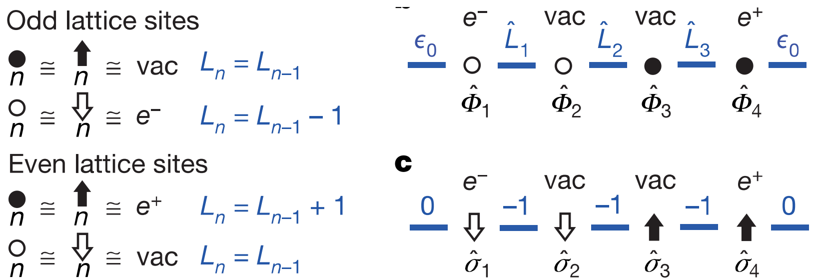
$$H = \frac{1}{2a}\sum_n [\sigma_n^+ L_n^+ \sigma_{n+1}^- + \text{h.c.}] + m\sum_n (-1)^n \sigma_n^z + \frac{g^2 a}{2}\sum_n L_n^2$$

$$L_n = \frac{E_n}{g}$$

Two Challenges:

1) Engineering three-body interactions
2) Preserve Gauss Law

$$L_n - L_{n-1} + \frac{1}{2}[\sigma_n^z + (-1)^n] = \text{const.}$$



# 1+1D Schwinger model with trapped ions

$$H = w\sum_n [\sigma_n^+ e^{i\theta_n}\sigma_{n+1}^- + \text{h.c.}] + \frac{m}{2}\sum_n (-1)^n \sigma_n^z + J\sum_n L_n^2$$

$$L_n - L_{n-1} = \frac{1}{2}\left[\sigma_n^z + (-1)^n\right]$$

$$\sigma_n^- \rightarrow \prod_{l<n} e^{i\theta_l}\sigma_n^-$$

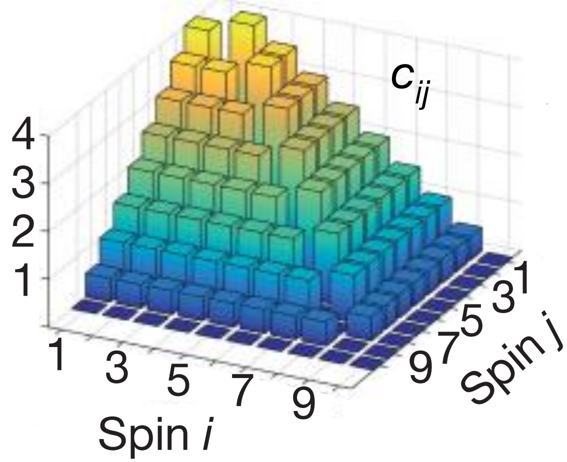
$$H = w\sum_{n=1}^{N-1}[\sigma_n^+\sigma_{n+1}^- + \text{h.c.}] + \frac{m}{2}\sum_{n=1}^{N} c_n\sigma_n^z + \frac{J}{2}\sum_{n=1}^{N-2}\sum_{l=n+1}^{N-1}\sigma_n^z\sigma_l^z$$

Particle-antiparticle hopping

Mass term

Gauge field

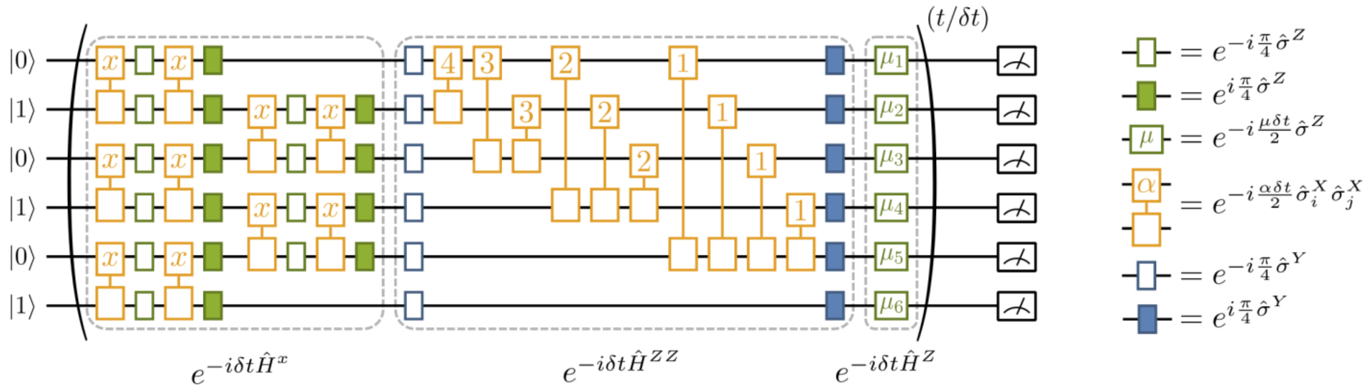
Implementation with long range interactions

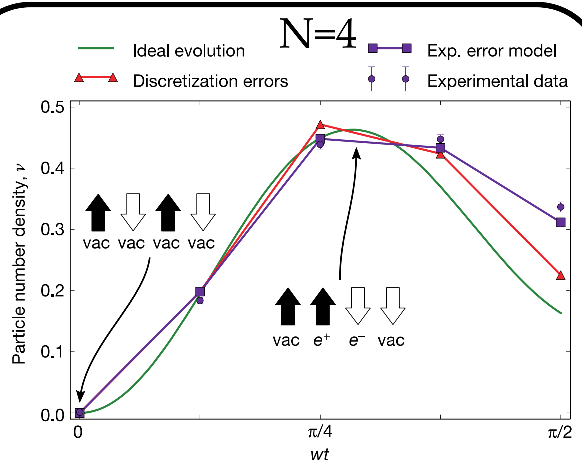




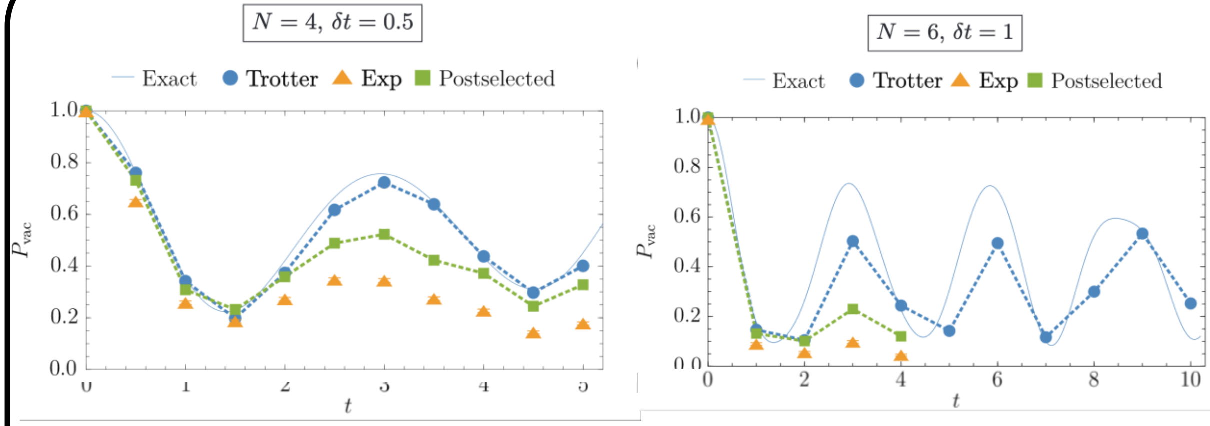
E. Martinez, et al., **Nature** 534, 516 (2016)
C. Mushik, et al., **NJP** 19, 103020 (2017)

# 1+1D Schwinger model: digital approach




E. Martinez, et al., **Nature** 534, 516 (2016)




N. Nhung, et al., **PRXQ** 3, 020324 (2022)

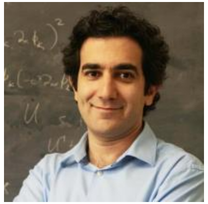
# Analog proposal for the 1+1D Schwinger model

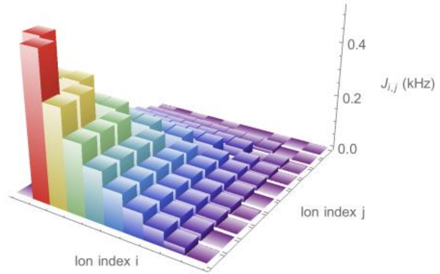
$$H = w\sum_{n=1}^{N-1}[\sigma_n^+\sigma_{n+1}^- + \text{h.c.}] + \frac{m}{2}\sum_{n=1}^{N} c_n\sigma_n^z + \frac{J}{2}\sum_{n=1}^{N-2}\sum_{l=n+1}^{N-1}\sigma_n^z\sigma_l^z$$

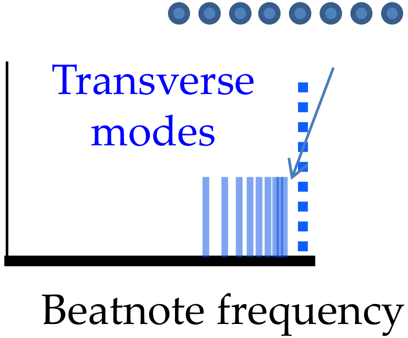
Particle-antiparticle hopping — Mass — Gauge field


Z. Davoudi


A. Seif


M. Hafezi

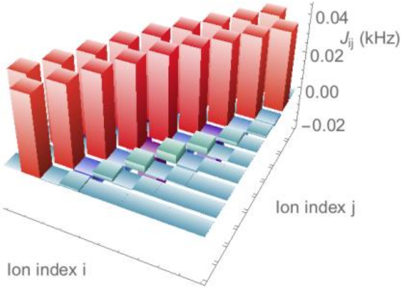


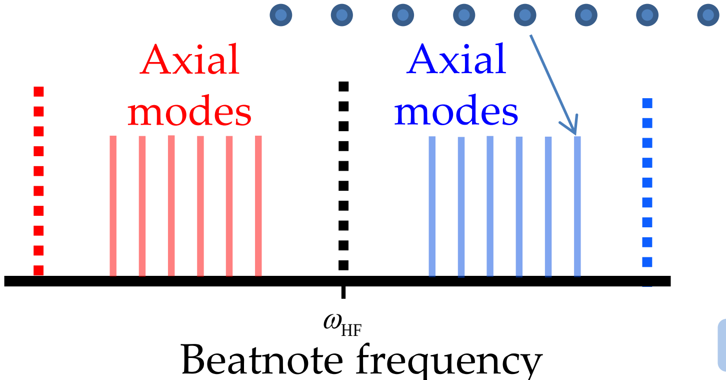



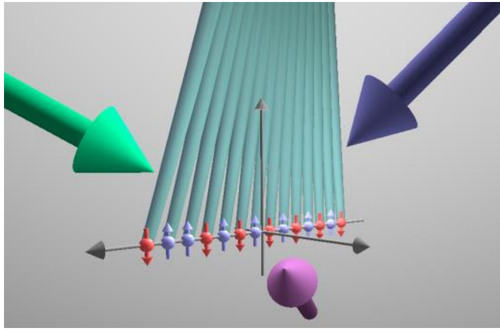


A. N. Shaw


C. Monroe

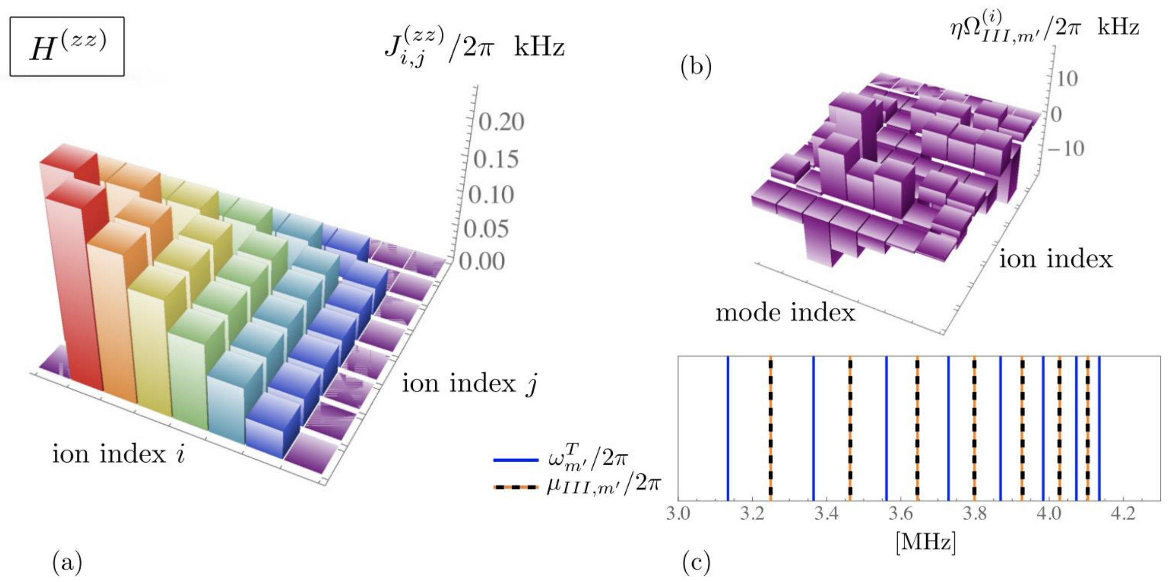


Z. Davoudi et al., PRR 2, 023015 (2020)

# Analog proposal for the 1+1D Schwinger model




Multi-amplitude and multi-frequency Optimization with full magnus expansion:

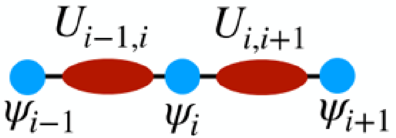
- Residual spin-phonon coupling
- Cross-talk between orthogonal normal modes
- Higher order processes

Z. Davoudi et al., PRR 2, 023015 (2020)

# The higher-order interaction route

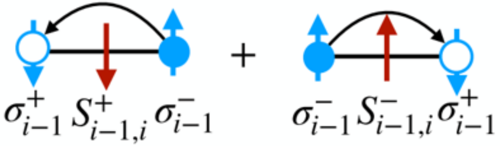
$$H_{\mathrm{U(1)}} = x \sum_{i=1}^{N_{\mathrm{stag}}-1} \left[\psi_i^\dagger U_i \psi_{i+1} + \mathrm{h.c.}\right] + \sum_{i=1}^{N_{\mathrm{stag}}-1} E_i^2 + \mu \sum_{i=1}^{N_{\mathrm{stag}}} (-1)^i \psi_i^\dagger \psi_i$$

hopping field mass




Quantum Link formulation

$$H_{\mathrm{QLM}} = J \sum_{i=1}^{N_{\mathrm{stag}}-1} \left[\sigma_i^+ S_i^+ \sigma_{i+1}^- + \mathrm{h.c.}\right] + \sum_{i=1}^{N_{\mathrm{stag}}-1} S_z^2 + \mu \sum_{i=1}^{N_{\mathrm{stag}}} (-1)^i \sigma_i^z$$



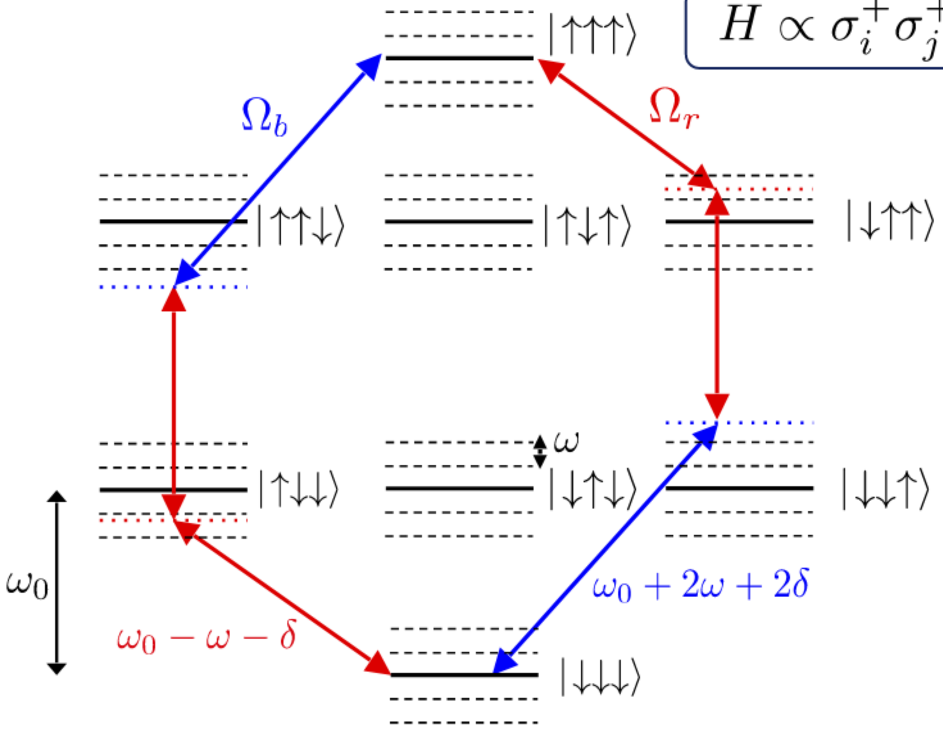

$$H_{\mathrm{Ion}} = J \sum_{i=1}^{N_{\mathrm{stag}}-1} \left[\sigma_{2i-1}^+ \sigma_{2i}^+ \sigma_{2i+1}^- + \mathrm{h.c.}\right] + \mu \sum_{i=1}^{N_{\mathrm{stag}}} (-1)^i \sigma_{2i-1}^z$$

$$H \sim \sigma_{i-1}^+ \sigma_i^+ \sigma_{i+2}^+$$

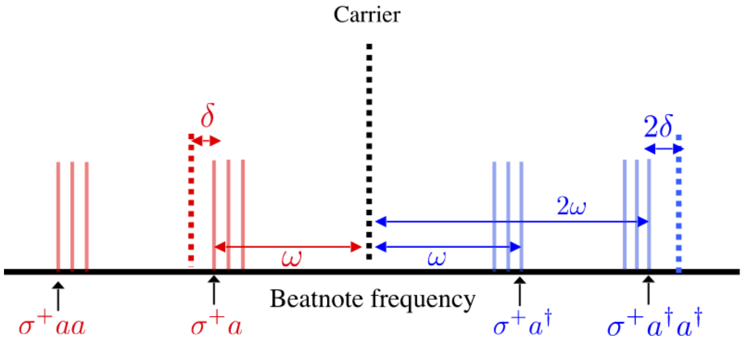
XXX gate, O. Katz et al., arXiv:2209.05691 (2022)

# Generalized Molmer-Sorensen scheme

$$H \propto \sigma_i^+ \sigma_j^+ \sigma_k^+$$








B. Andrade et al., QST 7 034001, (2022)

# Generalized Molmer-Sorensen scheme

Effective Hamiltonian in single mode approximation:

$$\mathcal{H}_{\text{eff}}^{(\sigma)} = -\frac{1}{4}\sum_i \frac{\eta_{\text{COM}}^2}{\delta}\left[\Omega_r^2(n+\frac{1}{2}) - \frac{1}{8}\eta_{\text{COM}}^2\Omega_b^2(n^2+n+1)\right]\sigma_i^z$$

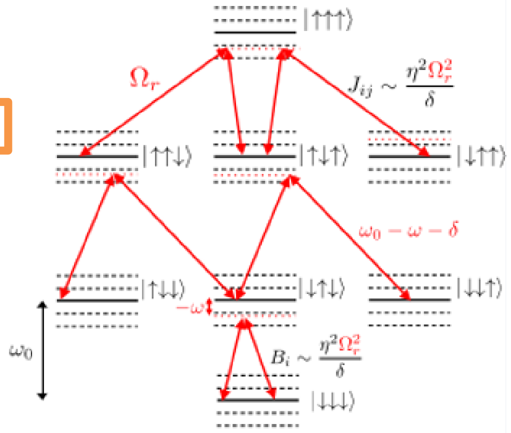
**ODD**

$$\mathcal{H}_{\text{eff}}^{(\sigma\sigma)} = \frac{1}{4}\sum_i\sum_{j\neq i} \frac{\eta_{\text{COM}}^2}{\delta}\left[\Omega_r^2 + \frac{1}{2}\eta_{\text{COM}}^2\Omega_b^2(n+\frac{1}{2})\right]\sigma_i^+\sigma_j^-$$

**ODD**

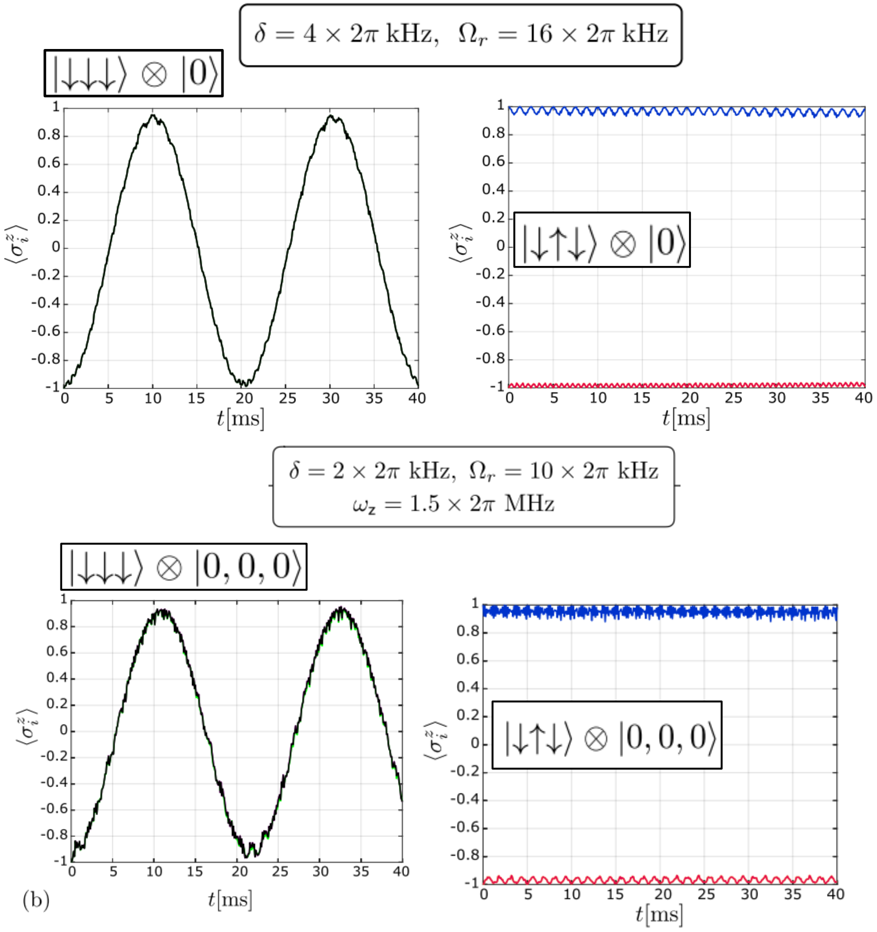
$$\mathcal{H}_{\text{eff}}^{(\sigma\sigma\sigma)} = \sum_{i,j,k}\left[\frac{\eta_{\text{COM}}^4}{16\delta^2}\Omega_r^2\Omega_b\sigma_i^+\sigma_j^+\sigma_k^+ + \text{h.c.}\right]$$

**EVEN**



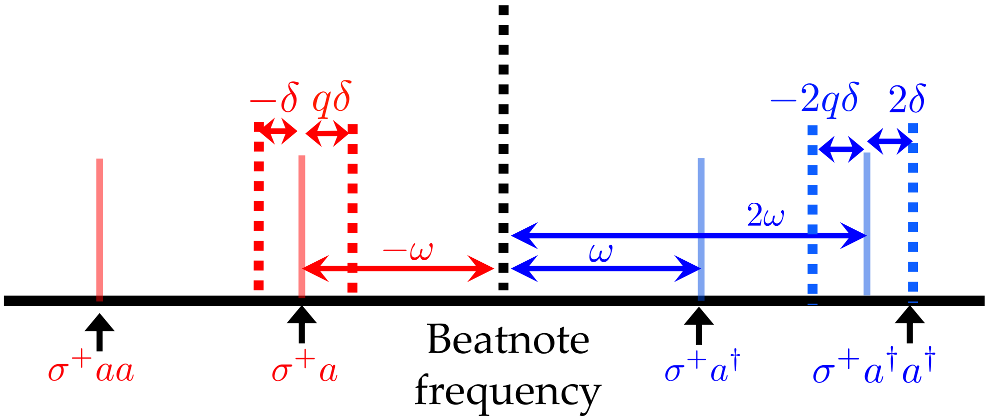

B. Andrade et al., QST 7 034001, (2022)

# Two-body term suppression




Multifrequency drive to suppress unwanted 2-body interactions

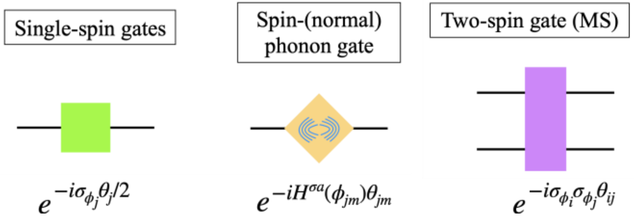
Single phonon mode




Three phonon modes

B. Andrade et al., QST 7 034001, (2022)

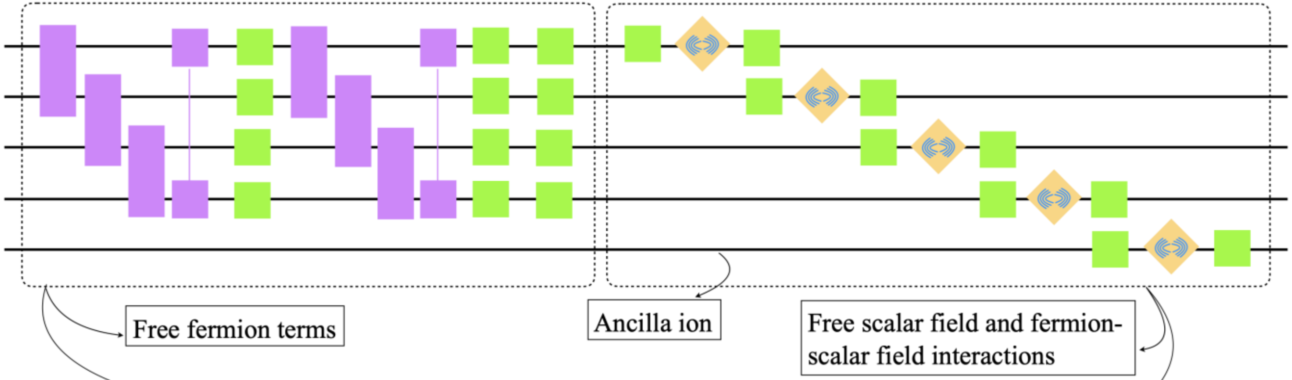
# Hybrid Analog-Digital simulation of Yukawa model



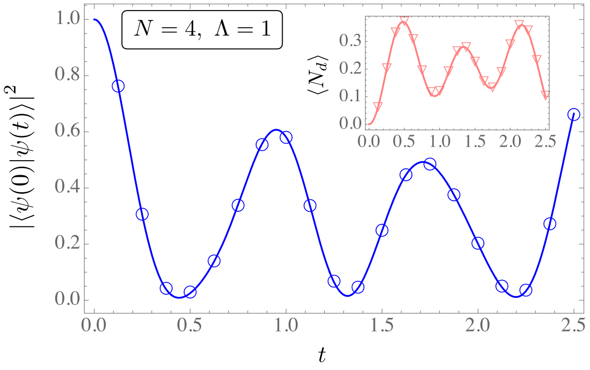

Z. Davoudi N. M. Linke

Spin → Fermions $\psi_i = \prod_{l<j} (i\sigma_l^z)\sigma_j^-$

Collective modes → scalar bosons $d_k^\dagger, d_k, \varphi_j$

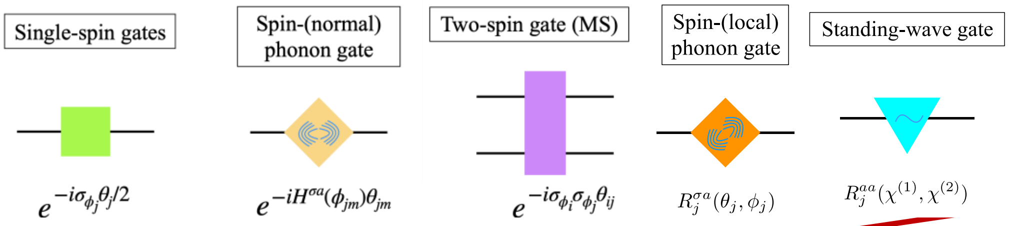



$$H_{\text{Yukawa}} = \sum_{j=1}^{N} \left[ \frac{i}{2b}(\psi_j^\dagger \psi_{j+1} - \psi_{j+1}^\dagger \psi_j) + m_\psi (-1)^j \psi_j^\dagger \psi_j \right] + \sum_{k=-N/2}^{N/2-1} \varepsilon_k \left( d_k^\dagger d_k + \frac{1}{2} \right) + gb \sum_{j=1}^{N} \psi_j^\dagger \varphi_j \psi_j$$




Z. Davoudi, et al., PRR 3, 043072 (2021)

# Spin-phonon realization of Schwinger model



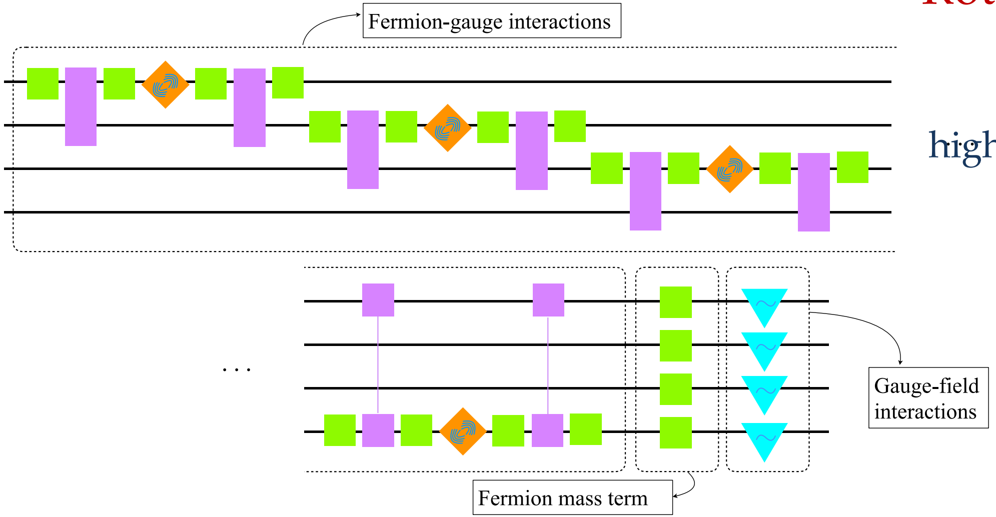

Gauge bosons local in space

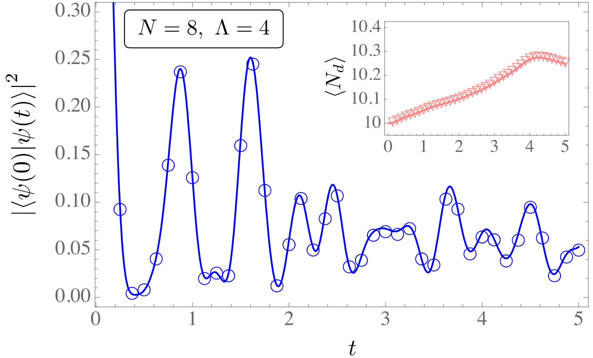
$$\frac{i}{2b}\sum_{j=1}^{N}(\psi_j^\dagger U_j^\dagger \psi_{j+1} - \psi_j U_j \psi_{j+1}^\dagger) + m\sum_{j=1}^{N}(-1)^j \psi_j^\dagger \psi_j + \frac{g^2 b}{2}\sum_{j=1}^{N} E_j^2 \text{ with } [E_j, U_{j'}] = U_j \delta_{j,j'}$$

Rotor algebra≠phonon algebra

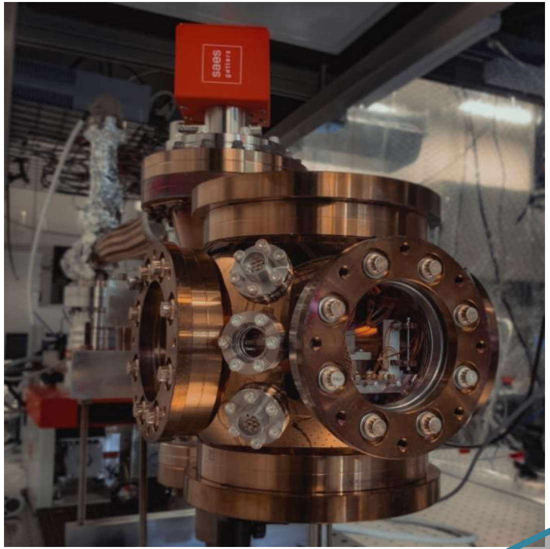
HOBM $\frac{g^2 b}{2}\sum_{j=1}^{N}\left[-2M(d_j^\dagger d_j) + (d_j^\dagger d_j)^2\right]$

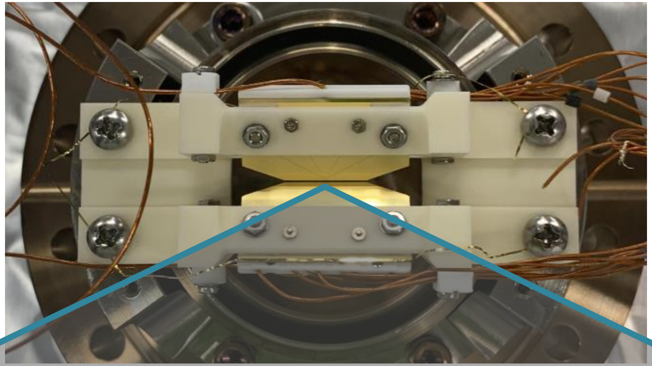
highly occupied bosonic mode, PRA 94,052321 (2016)

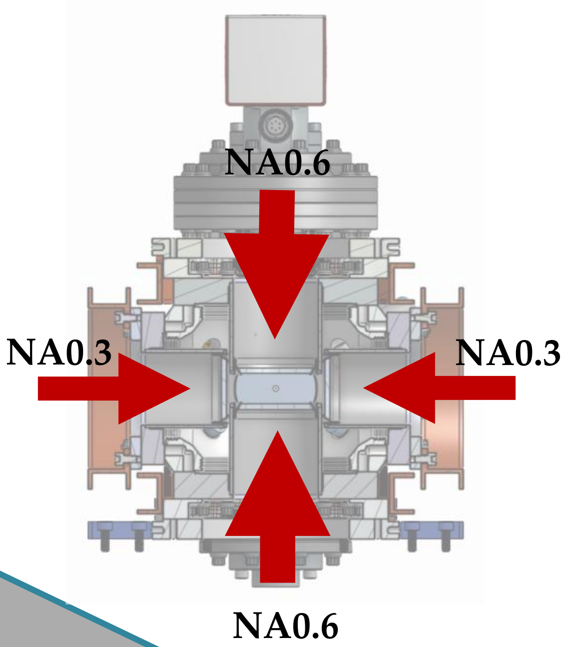


# Experimental System at Rice

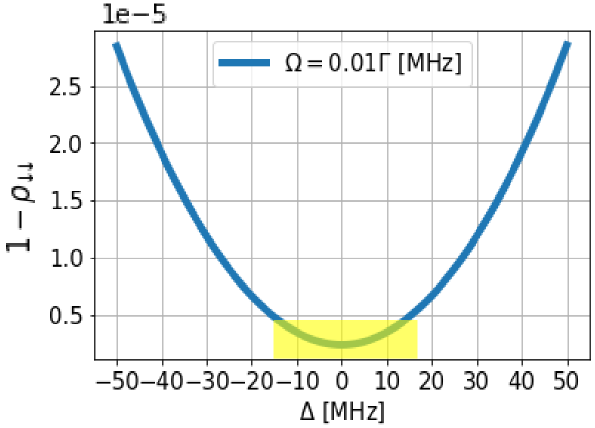




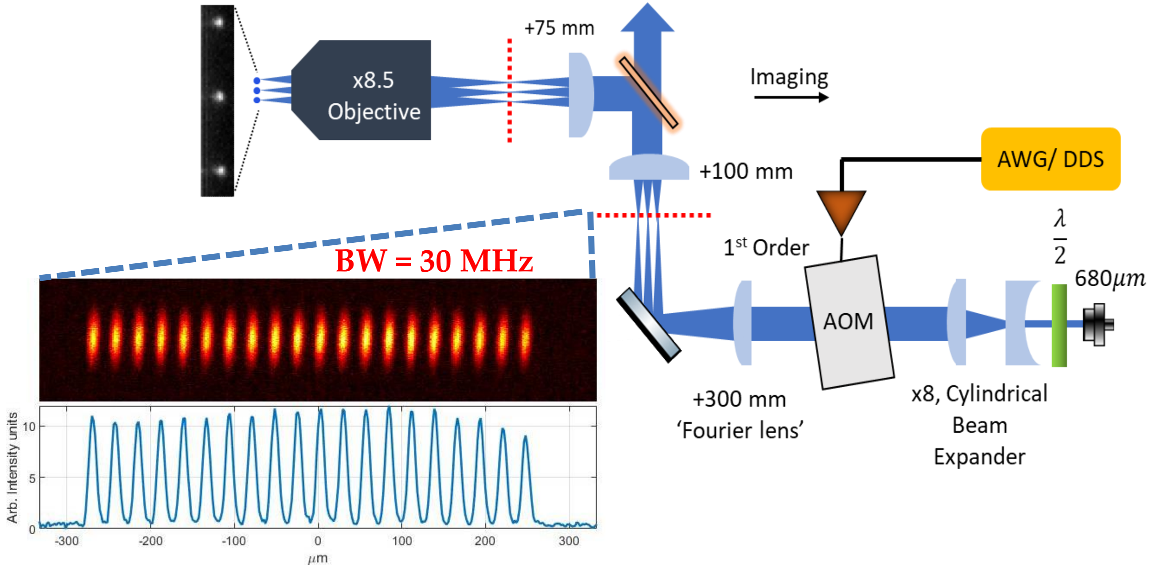


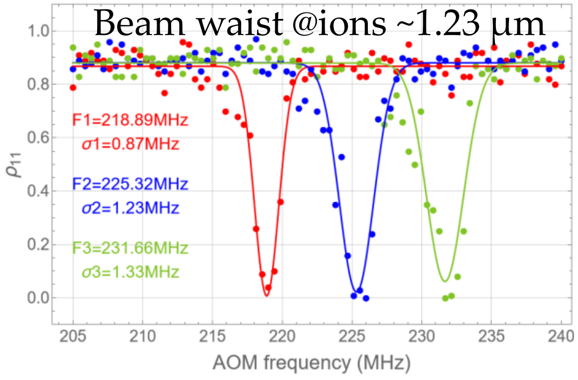

# Individual Optical pumping

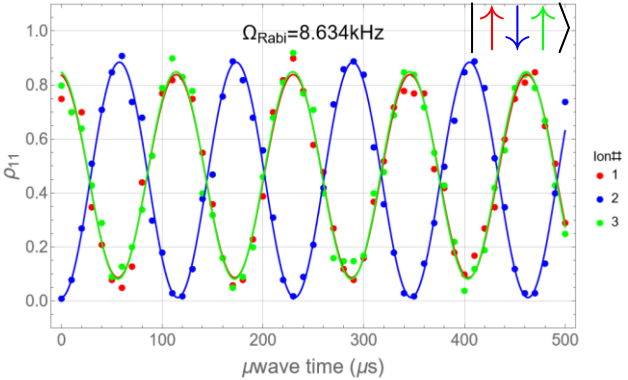
OP weakly dependent on frequency




Simple Tweezer array approach based on Elliptical beams

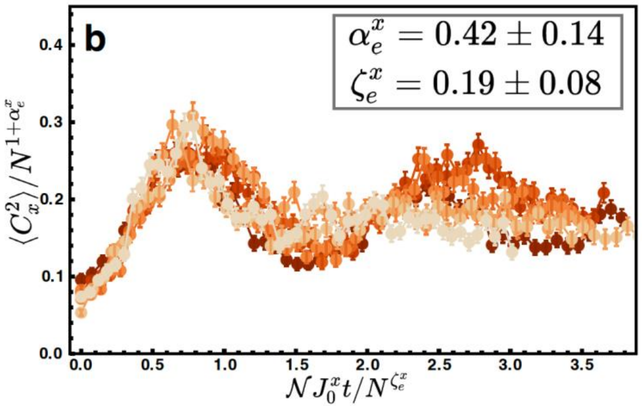


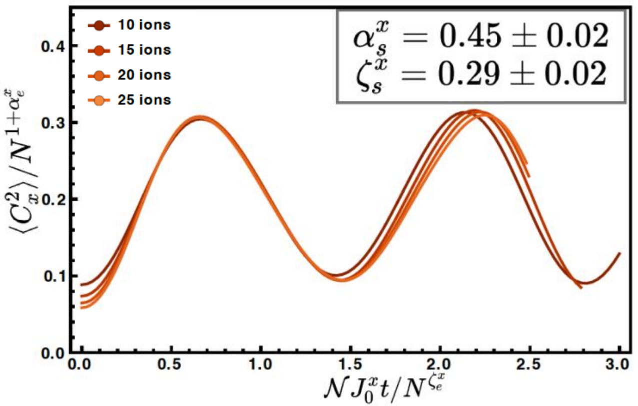



# Other Directions

## Critical non-equilibrium dynamics



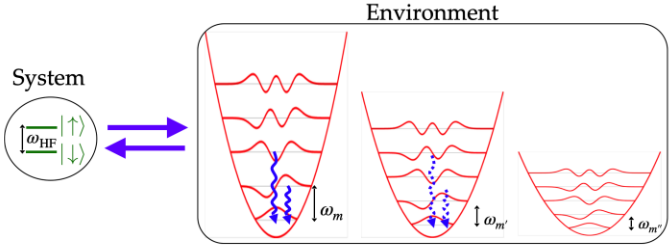

M. Maghrebi

C. Monroe

W. Morong

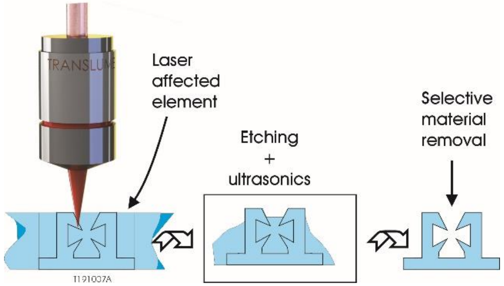
A. De

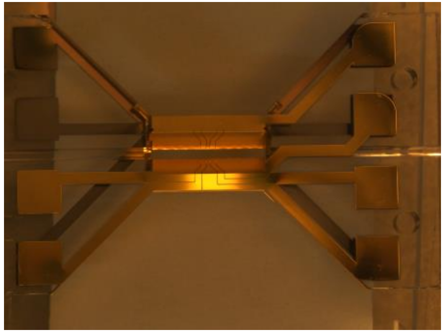
## Quantum Chemistry/Electron transfer




P. Wolynes

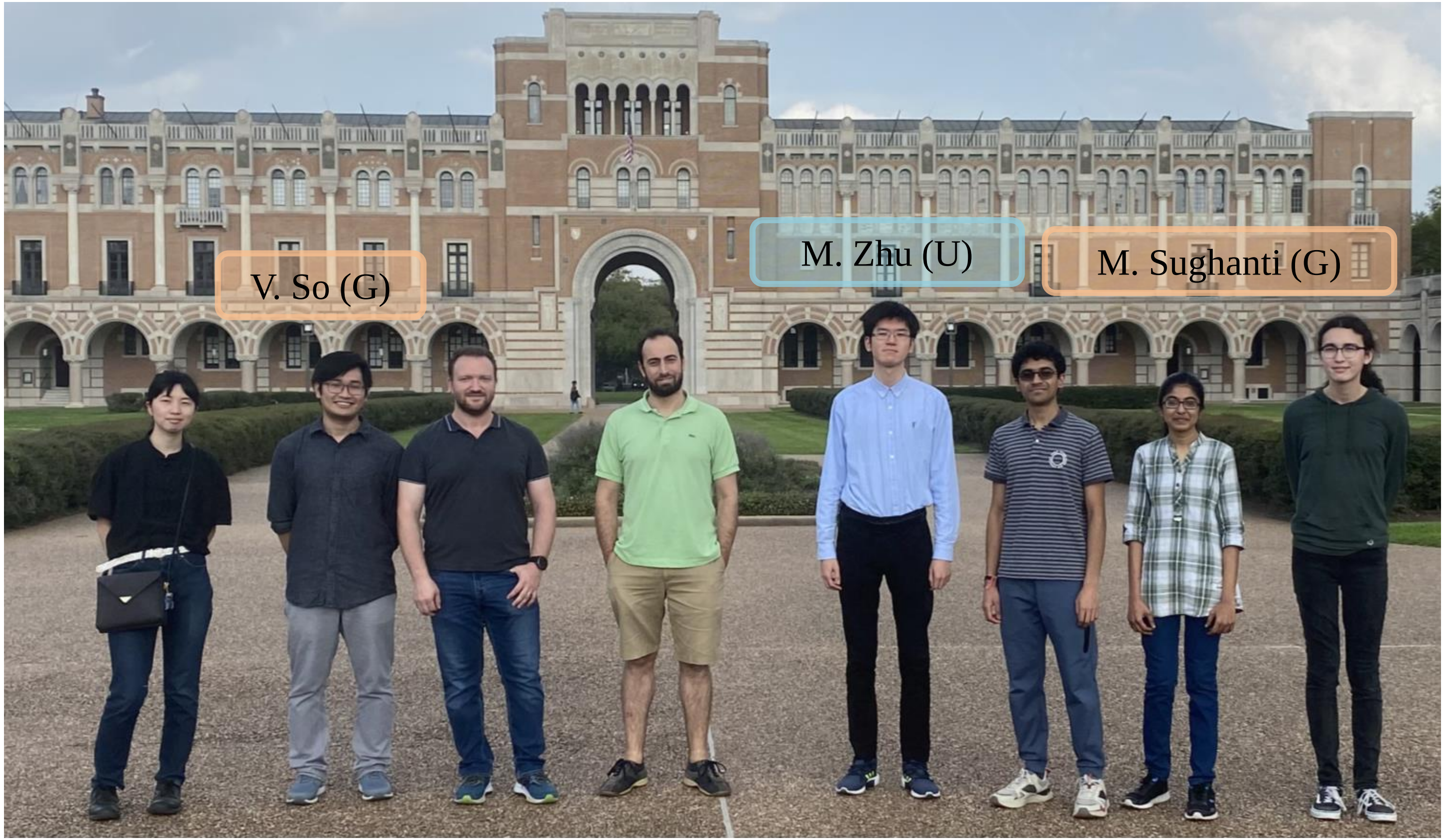
## Ion Trapping made easy: Monolithic trap



N. M. Linke + Translume

# Acknowledgments



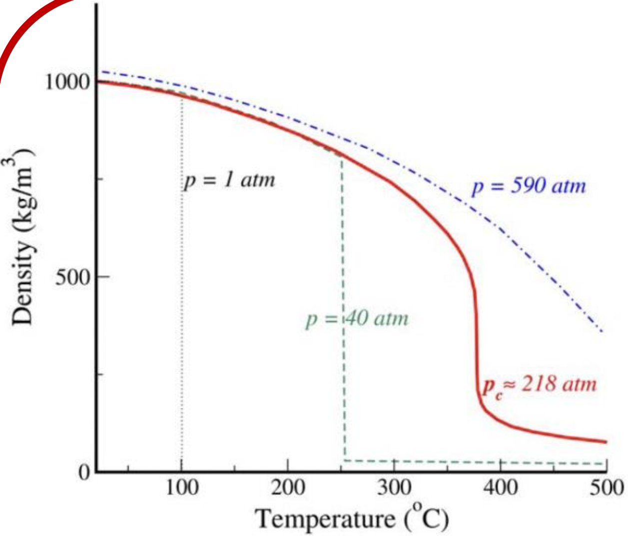

A. Tanaka (U)

R. Zhuravel (P)

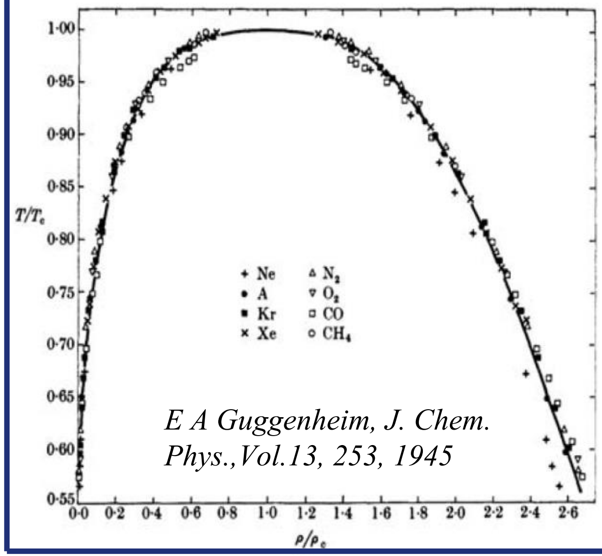
A. Menon (G)

A. Sheffield (U)

# Phase transitions and criticality




At 218 atm and 374$^0$C water and vapor co-exists. **Critical point for the phase transition.**



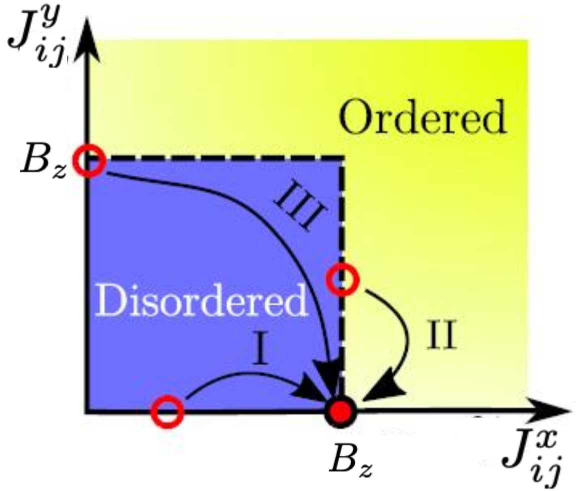

Density and Temperatures for different systems scaled with a **"critical exponent"** to collapse → **"Universal properties" of phase transition**.

Can we find universal scaling in non-equilibrium quantum systems?

# Non equilibrium criticality in quench dynamics

Prototype model for long-range interaction: Lipkin-Meshkov-Glick model (LMG)
(a.k.a. "all-to-all" interactions)

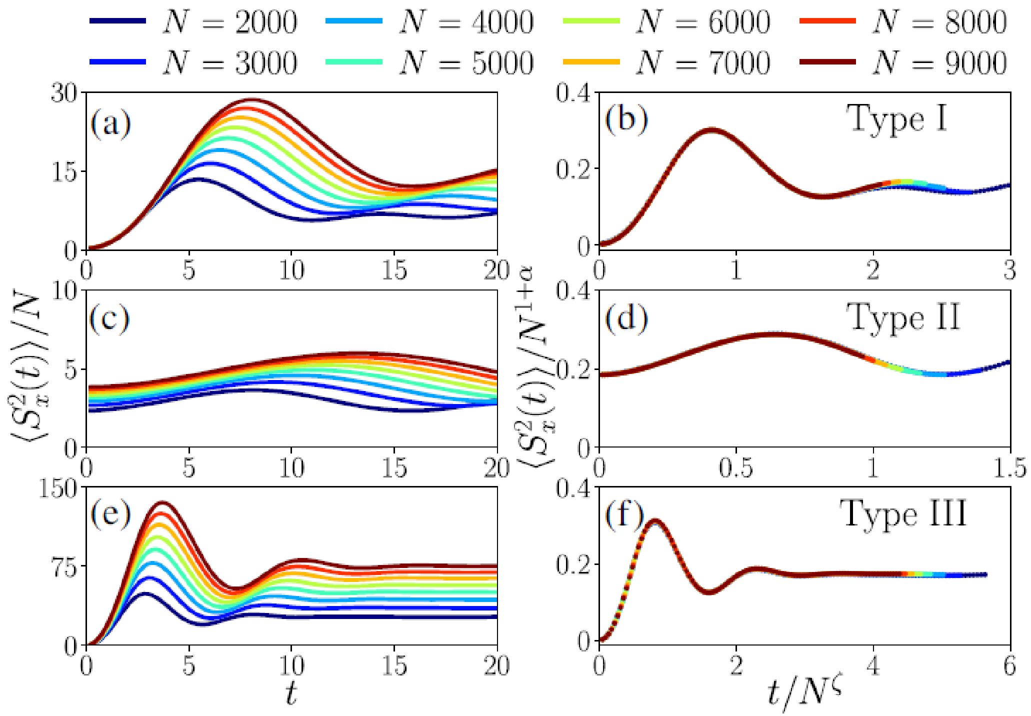
$$H = -\frac{1}{N}\sum_{i<j} J^x_{ij}\sigma^x_i\sigma^x_j + J^y_{ij}\sigma^y_i\sigma^y_j - B_z\sum_i \sigma^z_i$$



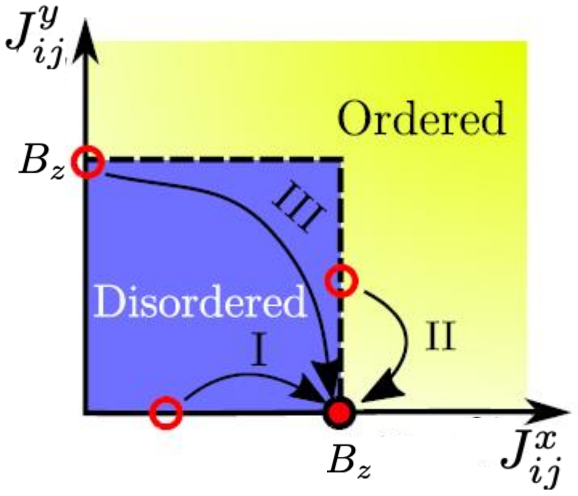

Order Parameters: $< S_x >, < S_y >$

Observables: $S_a = \frac{1}{2}\sum_i \sigma^a_i,$ $\frac{1}{N}\langle S^2_x(t)\rangle = N^\alpha f\left(\frac{t}{N^\zeta}\right)$

Paraj Titum, Mohammad F. Maghrebi, Phys. Rev. Lett. **125**, 040602. (2020)

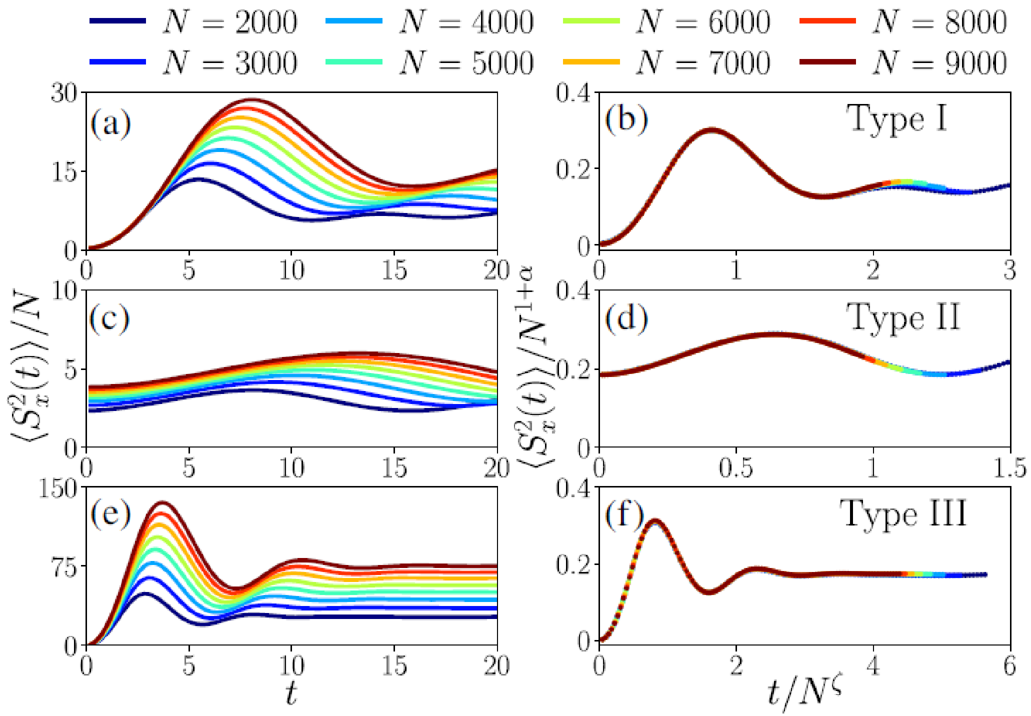


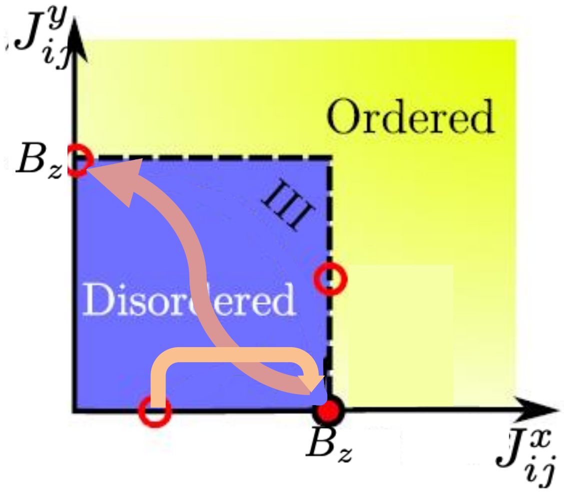

Depending on the initial state, the LMG dynamics scales with different exponents




| | Type I | Type II | Type III | TCP | QCP |
|---|---|---|---|---|---|
| $\zeta$ | $\frac{1}{4}$ | $\frac{1}{3}$ | $\frac{1}{6}$ | $\frac{1}{4}$ | $\frac{1}{3}$ |
| $\alpha$ | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{2}{3}$ | $\frac{1}{2}$ | $\frac{1}{3}$ |
| $T_{\text{eff}}^{\text{IR}}$ | Finite | 0 | $\sim N^{1/3}$ | $T_c$ | 0 |

Adiabatically preparing a critical state is experimentally expensive.



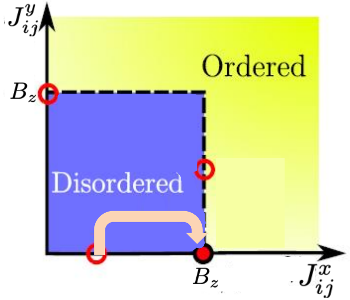



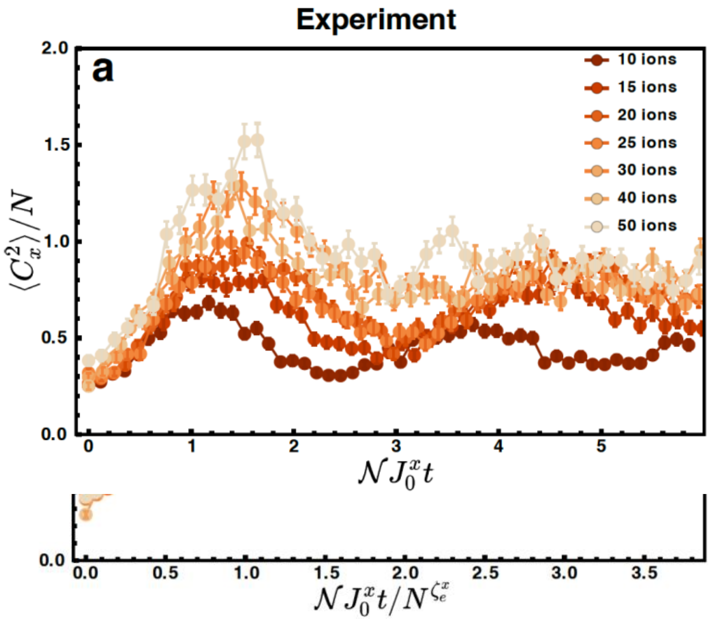

| | Type I | Type II | Type III | TCP | QCP |
|---|---|---|---|---|---|
| $\zeta$ | $\frac{1}{4}$ | $\frac{1}{3}$ | $\frac{1}{6}$ | $\frac{1}{4}$ | $\frac{1}{3}$ |
| $\alpha$ | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{2}{3}$ | $\frac{1}{2}$ | $\frac{1}{3}$ |
| $T_{\mathrm{eff}}^{\mathrm{IR}}$ | Finite | 0 | $\sim N^{1/3}$ | $T_c$ | 0 |

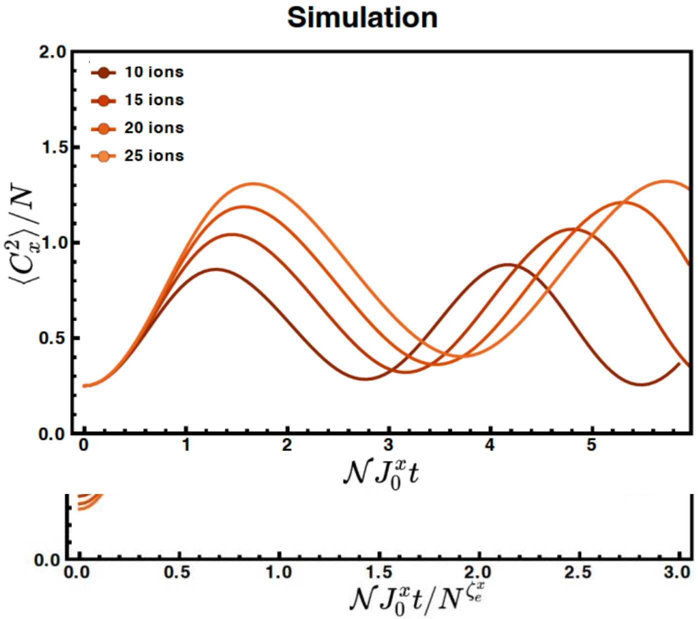
Double Quench Approach

# Type I quench

$| \downarrow_z \downarrow_z \downarrow_z \ \dots \ \downarrow_z >$ → $H = \sum_{ij} J_{ij} \sigma_x^i \sigma_x^j + B_z \sum_i \sigma_z^i$ → $< S_x^2 >$




Critical exponents consistent with a thermal phase transition

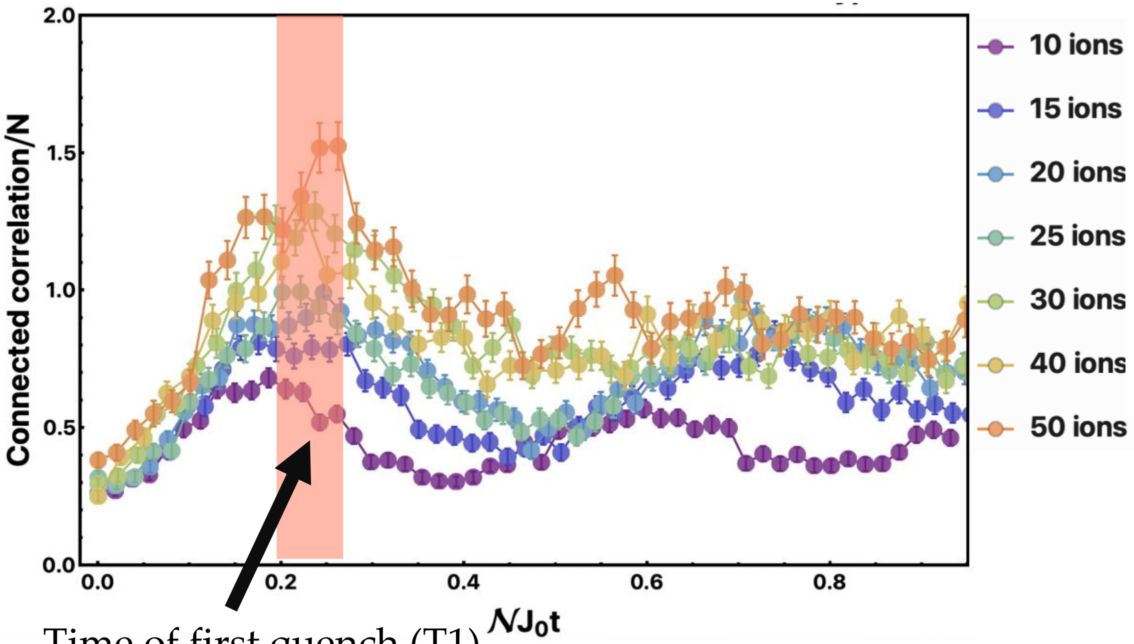
$$\mathcal{N} = \frac{\sum_{ij} J_{ij}}{N - 1}$$

# Double quench

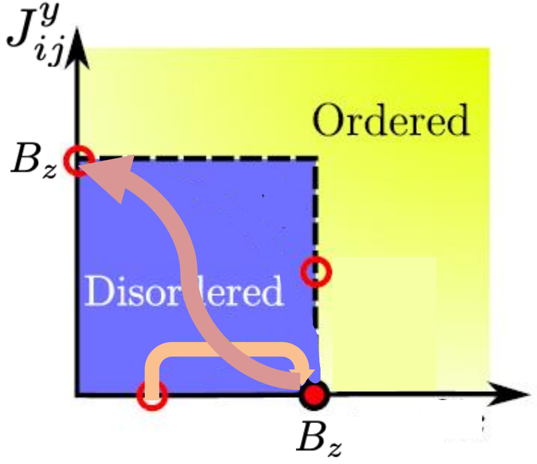
$$|\downarrow_z\downarrow_z\downarrow_z \ \dots \downarrow_z> \rightarrow H = \sum_{ij} J_{ij}\sigma_x^i\sigma_x^j + B_z\sum_i \sigma_z^i \rightarrow H = \sum_{ij} J_{ij}\sigma_y^i\sigma_y^j + B_z\sum_i \sigma_z^i \rightarrow < S_y^2 >$$

(T1)

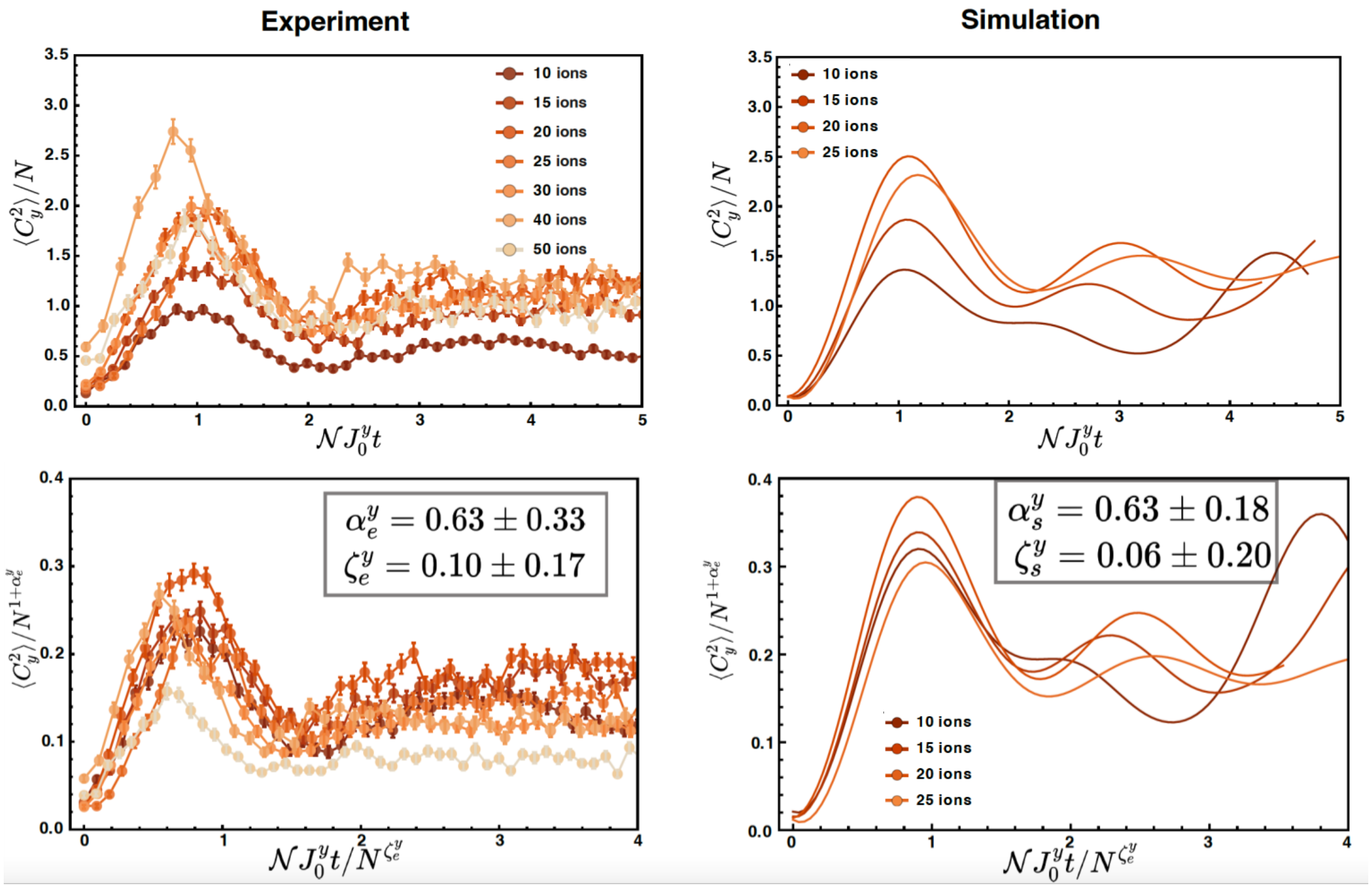
Unscaled critical fluctuation after type 1 quench




Time of first quench (T1)



# Critical scaling behavior after double quench with 10-50 ions




Critical exponents consistent with a non-equilibrium phase transition.

# Hierarchy of quenches

- One can keep doing multiple quenches.
- There are different universality classes for different sequence of quenches
- The scaling exponents are related by recursive relations

$$\alpha_D^{(n+1)} = \frac{1+\alpha_S^{(n)}}{2},$$
$$\alpha_S^{(n+1)} = \alpha_S^{(n)},$$
$$\zeta^{(n+1)} = \frac{1-\alpha_S^{(n)}}{4},$$

| | Type-I-III-III-... | | | Type-II-III-III-... | | | Type-III-III-III-... | | |
|---|---|---|---|---|---|---|---|---|---|
| $k$ | $\alpha_D^{(k)}$ | $\alpha_S^{(k)}$ | $\zeta^{(k)}$ | $\alpha_D^{(k)}$ | $\alpha_S^{(k)}$ | $\zeta^{(k)}$ | $\alpha_D^{(k)}$ | $\alpha_S^{(k)}$ | $\zeta^{(k)}$ |
| 1 | 1/2 | 0 | 1/4 | 1/3 | −1/3 | 1/3 | 1/3 | −1/3 | 1/3 |
| 2 | 3/4 | 1/2 | 1/8 | 2/3 | 1/3 | 1/6 | 2/3 | 1/3 | 1/6 |
| 3 | 7/8 | 3/4 | 1/16 | 5/6 | 2/3 | 1/12 | 5/6 | 2/3 | 1/12 |
| 4 | 15/16 | 7/8 | 1/32 | 11/12 | 5/6 | 1/24 | 11/12 | 5/6 | 1/24 |
| 5 | 31/32 | 15/16 | 1/64 | 23/24 | 11/12 | 1/48 | 23/24 | 11/12 | 1/48 |
| 6 | 63/64 | 31/32 | 1/128 | 47/48 | 23/24 | 1/96 | 47/48 | 23/24 | 1/96 |
| 7 | 127/128 | 63/64 | 1/256 | 95/96 | 47/48 | 1/192 | 95/96 | 47/48 | 1/192 |
| 8 | 255/256 | 127/128 | 1/512 | 191/192 | 95/96 | 1/384 | 191/192 | 95/96 | 1/384 |

# Acknowledgments


A. De


W. Morong→AWS


C. Monroe


M. Maghrebi


P. Cook


D. Paz


W. L. Tan → IonQ

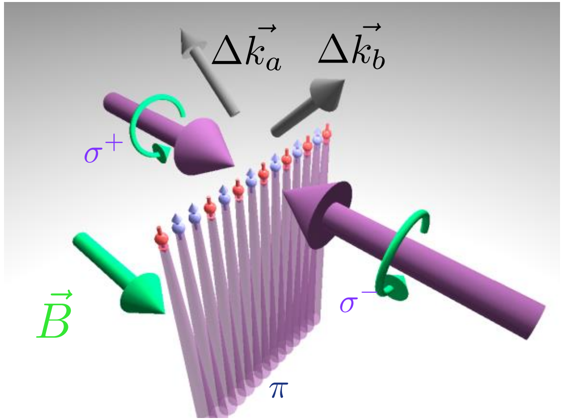

A. V. Gorshkov


P. Titum

# New Opportunities in Quantum Simulation

QAOA, PNAS 117 (41), 25396 (2020)
MB Dephasing, PRL 125, 120605 (2020)
Confinement, Nature Phys. 17, 742 (2021)

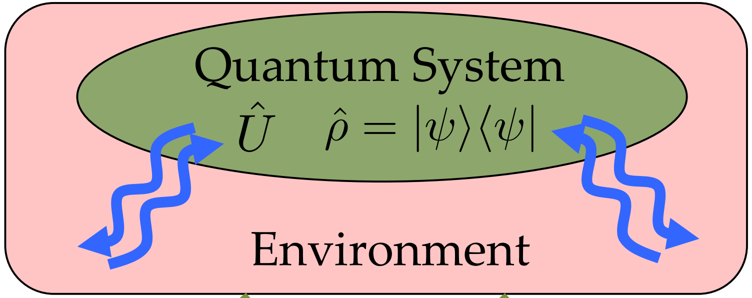
- Global Interaction Control
- One set of normal modes




RICE

- Quantum magnetism models
- Optimization problems
- Quantum Spin glasses
- High Energy Physics
- **Driven-Dissipative quantum systems**

# Dissipative Many-body Systems




Dissipative Phase Transitions (DPT)

$$\frac{\partial \rho}{\partial t} = \frac{1}{i\hbar}[H, \rho] + \mathcal{L}(\rho)$$

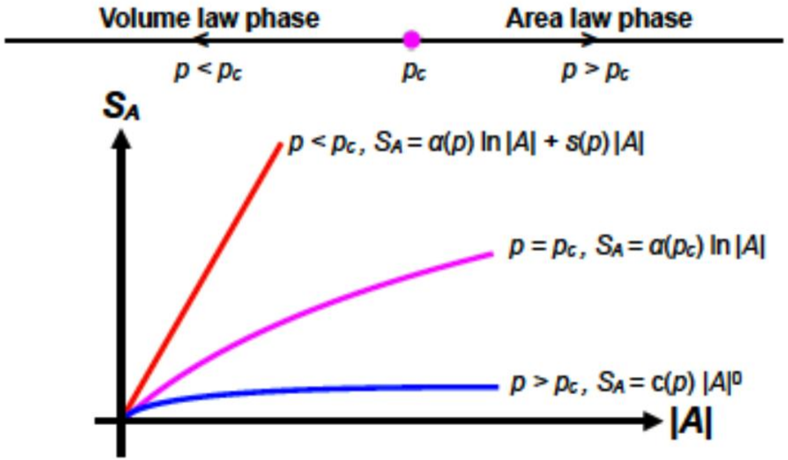
Properties of the Average state

$$\langle O \rangle = \mathrm{Tr}(\rho O)$$


L. M. Sieberer, et al., Rep. Prog. in Phys. 79, 096001 (2016).
T. E. Lee, et al., Phys. Rev. Lett.110, 257204 (2013).
J. Jin, et al., Phys. Rev. X 6, 031011 (2016).
M. F. Maghrebi, et al., Phys. Rev. B 93, 014307 (2016) ….


Measurement-induced phase transitions

'T)



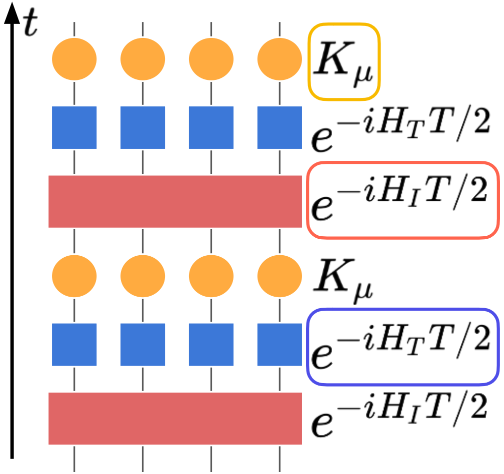

opy

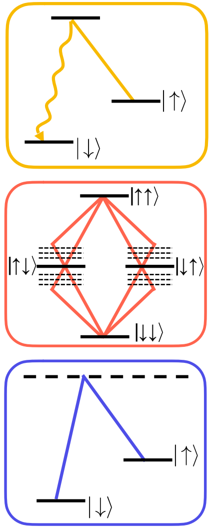
$\rho_A)$

)

…

# Dissipative Floquet Systems



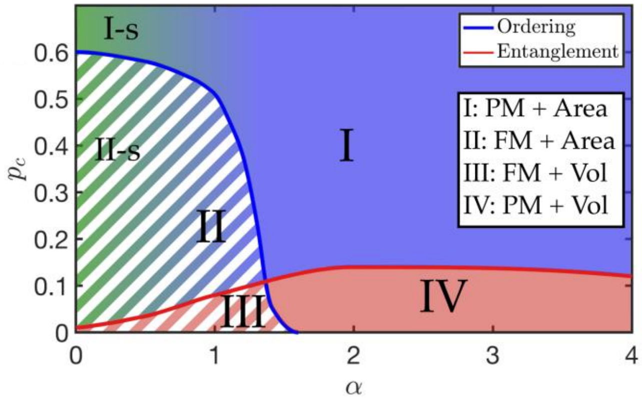

$$K_{i,0} = \sqrt{p}|\downarrow\rangle\langle\downarrow|_i \qquad K_{i,2} = \sqrt{1-p}\,\mathbf{1}_i$$
$$K_{i,1} = \sqrt{p}|\downarrow\rangle\langle\uparrow|_i$$

$$H_I = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x, \quad J_{ij} \sim \frac{J_0}{|i-j|^\alpha}$$

$$H_T = B_z \sum_i \sigma_i^z$$

DPT
Order-Disorder ?

$$X^2 = \frac{1}{L}\mathrm{Tr}(\rho_{ss}\sum_{i\neq j}\sigma_i^x\sigma_j^x)$$




MIPT
Volume-Area law ?

$$S_A = -\mathrm{Tr}(\rho_A \log \rho_A)$$

P. Sierant et. al., Quantum 6, 638 (2022)

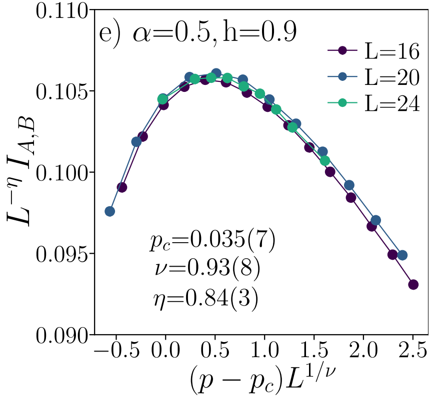
# Dissipative and Measurement-induced PTs

**Questions:**

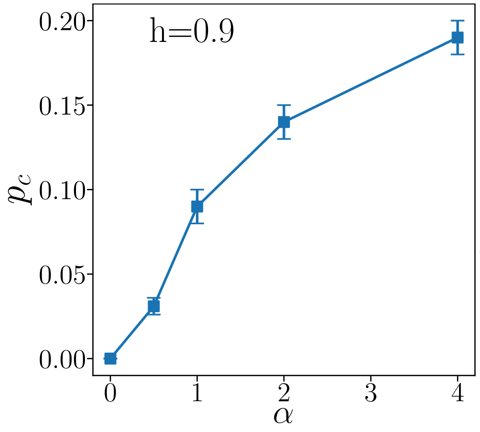
- Are these transitions present in a Hamiltonian system with long-range interactions?
- Are they connected or exclusive?

## Mutual information

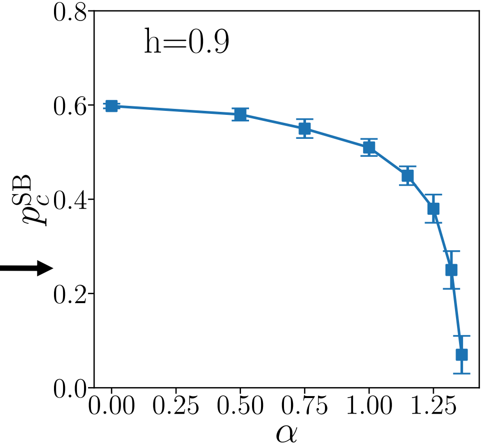
$$I_{A,B} = S(A) + S(B) - S(A \cup B)$$




**MIPT**

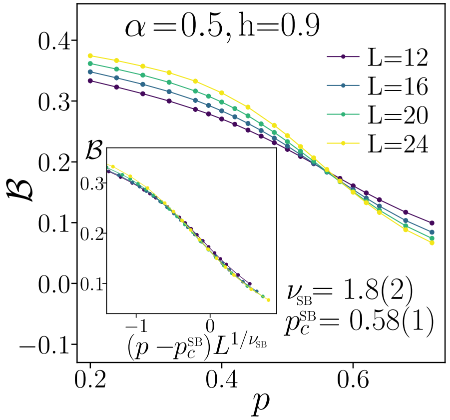



**DPT**




## Binder Cumulant

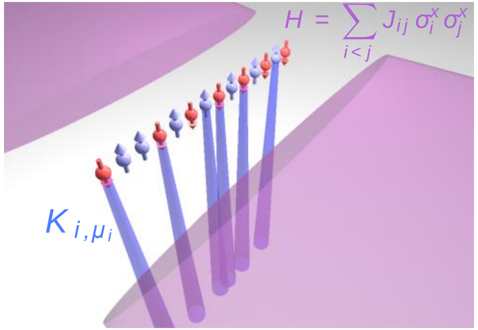
$$\mathcal{B} = 1 - \frac{\langle S_x^4 \rangle}{\langle S_x^2 \rangle^2}$$

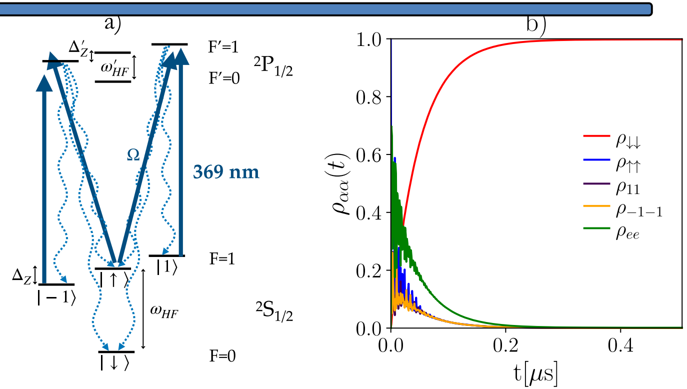


# Experimental Considerations

**DPT**:

Global Long-range Interactions
+
Local Optical Pumping



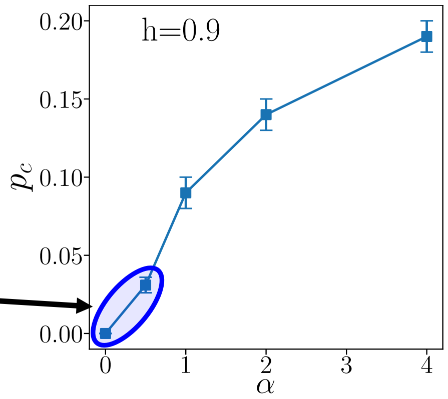




**MIPT**:

1) Detecting $S(\rho_A)$

2) Postselection→$2^{pLT}$ measurements

3) Detect individual qubits with negligible crosstalks




[P. Sierant et. al., Quantum 6, 638 (2022)]

# Acknowledgments

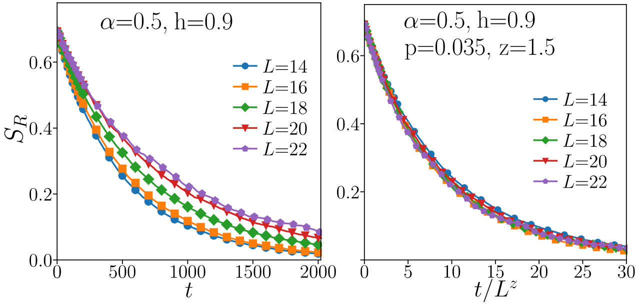
    

| Roman Zhuravel | Visal So | Abhishek Menon | Midhuna D. Sughanti | April Sheffield |
|---|---|---|---|---|
| (Postdoc) | (Grad Student) | (Grad Student) | (Grad Student) | (Undergraduate) |

Collaborators :

- Marcello Dalmonte
- Rosario Fazio
- Piotr Sierant
- Giuliano Chiriacò
- Federica Surace
- Xhek Turkeshi
- Zohreh Davoudi
- Mohammad Hafezi
- Tobias Grass
- Barbara Andrade
- Alireza Seif
- Norbert Linke

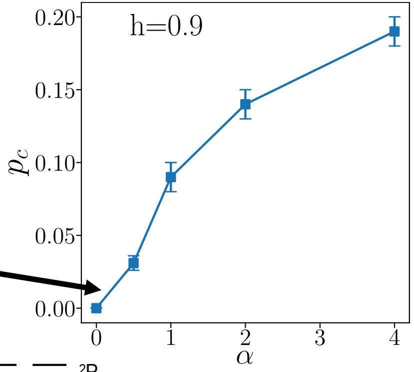
# Experimental Considerations




## 1) Detecting $S(\rho_A)$ of an entangled Ancilla

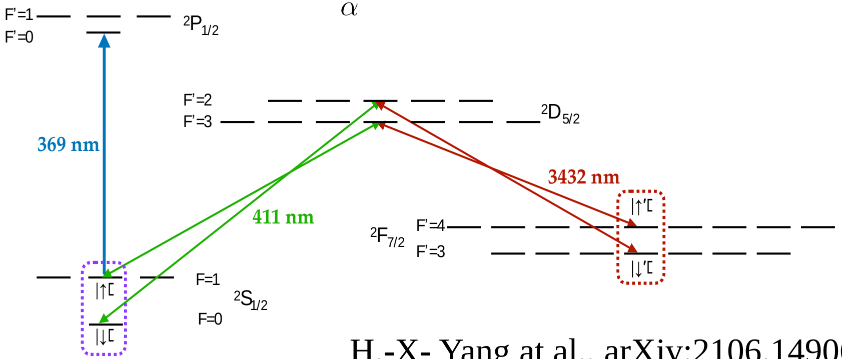
M. J. Gullans and D. A. Huse, PRL 125 (2020)

C. Noel et al., arXiv:2106.05881 (2021)




## 2) $2^{pLT}$ overhead manageable if $\alpha$ and, therefore, $p_c$ is decreased

## 3) Qubit hiding to avoid crosstalks during measurements



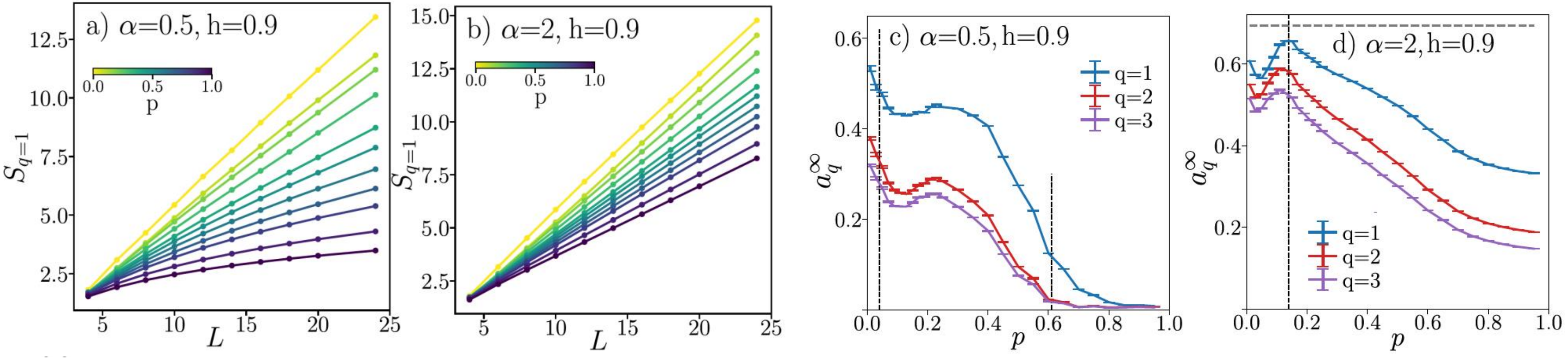

H.-X- Yang at al., arXiv:2106.14906 (2021)

# Participation Entropies

$$S_q = \frac{1}{1-q} \ln \left( \sum_{\beta=1}^{2^L} |\psi_\beta|^{2q} \right)$$

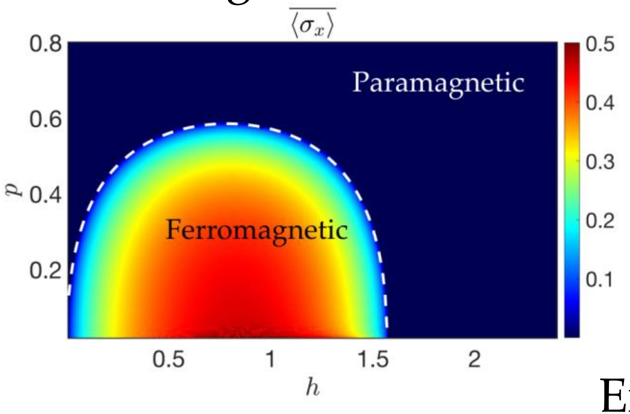
The scaling with L of $S_q$ distinguishes if wave functions that are delocalized, multifractal and localized.

$$a_q(L) \sim a_q^\infty + b_1/L + b_2/L^2$$



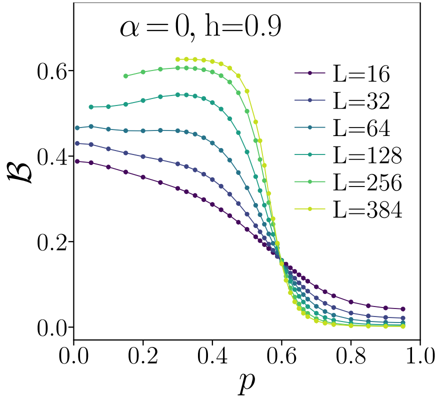
# Dissipative Symmetry-Breaking Phase transition

## Magnetization

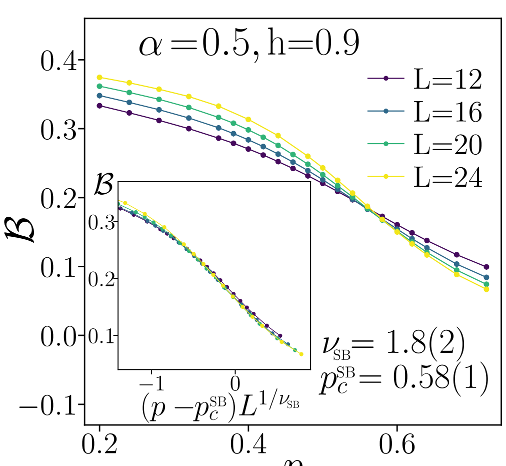


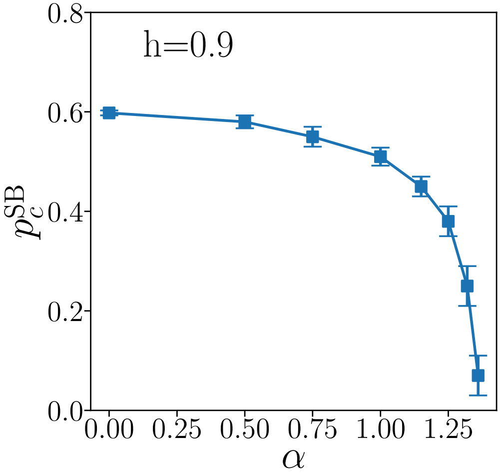

## Cluster mean field for $\alpha = 0$

## Binder cumulant

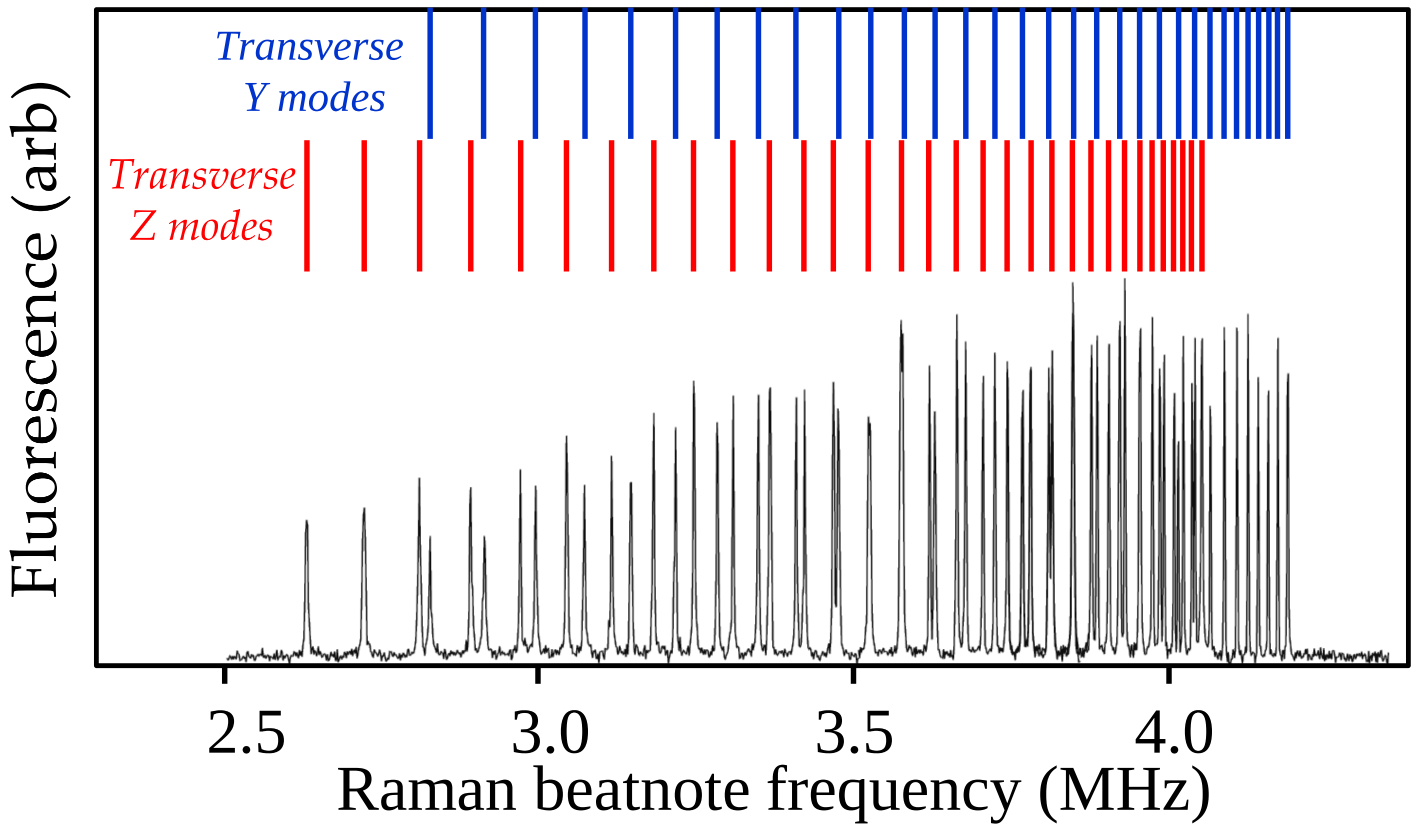



## Exact Diagonalization $\alpha > 0$



# Self-organized Ion crystals

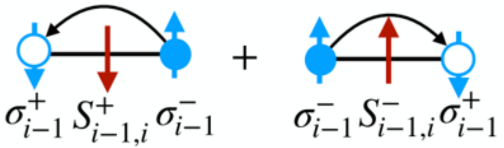


# From Spin models to HEP models

$$H_{\text{Ion}} = J \sum_{i=1}^{N_{\text{stag}}-1} \left[\sigma^+_{2i-1}\sigma^+_{2i}\sigma^-_{2i+1} + \text{h.c.}\right] + \mu \sum_{i=1}^{N_{\text{stag}}} (-1)^i \sigma^z_{2i-1}$$

$$H_{\text{QLM}} = J \sum_{i=1}^{N_{\text{stag}}-1} \left[\sigma^+_i S^+_i \sigma^-_{i+1} + \text{h.c.}\right] + \sum_{i=1}^{N_{\text{stag}}-1} S^2_z + \mu \sum_{i=1}^{N_{\text{stag}}} (-1)^i \sigma^z_i$$

$$H \sim \sigma_{i-1}\sigma_i\sigma_{i+2}$$



# Laser-ion interactions