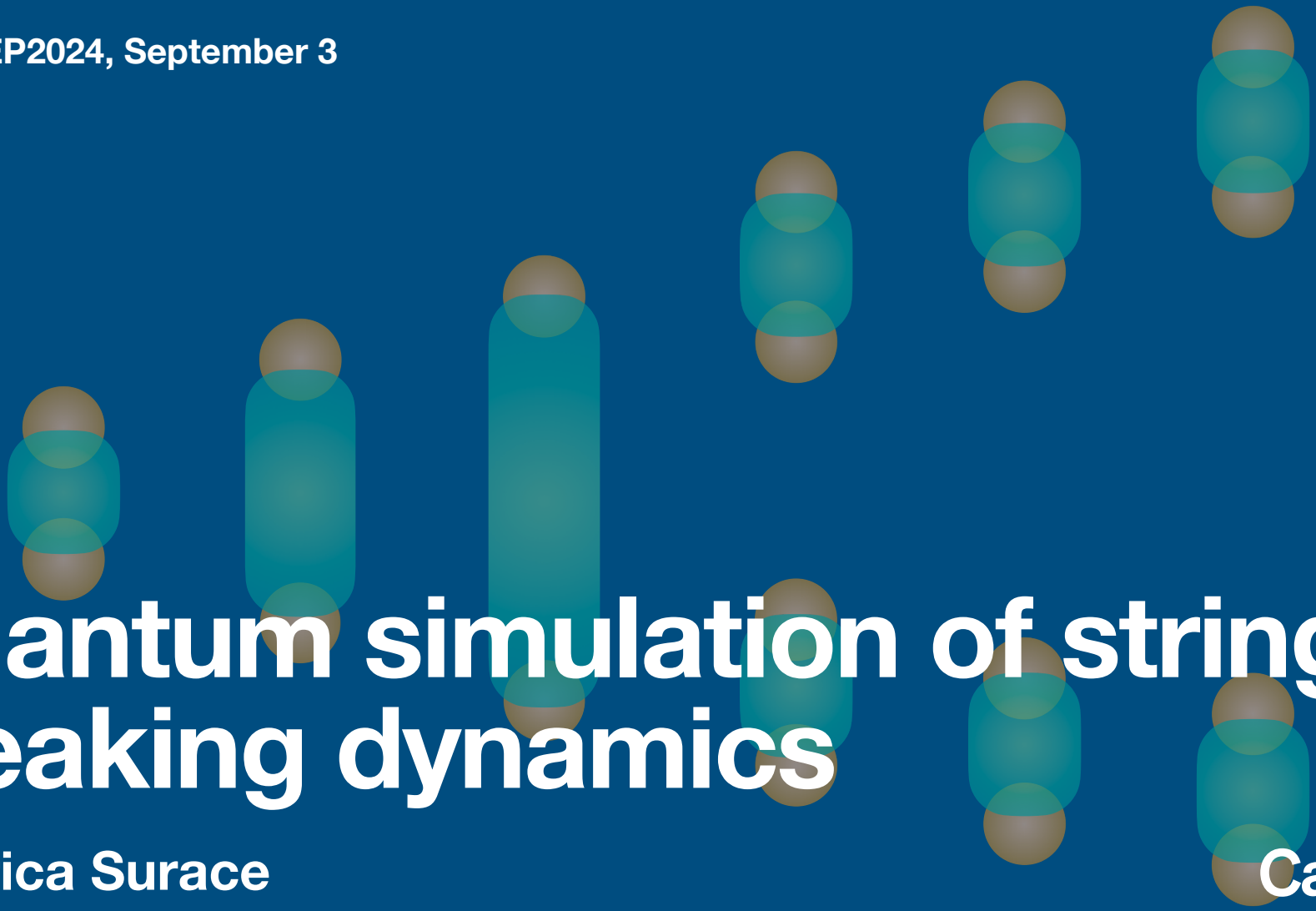
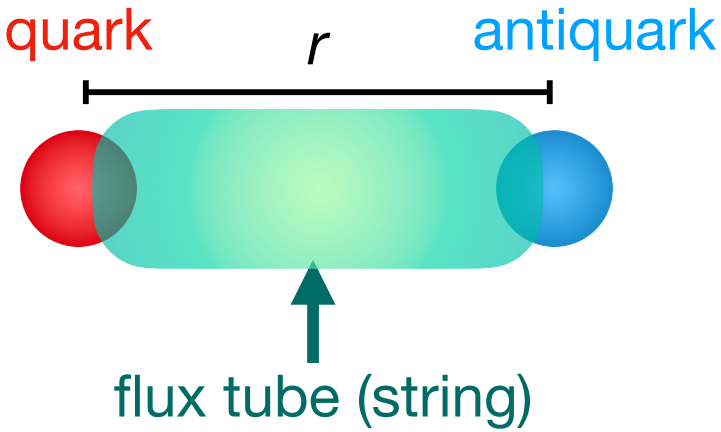
QuantHEP2024, September 3



Quantum simulation of string breaking dynamics

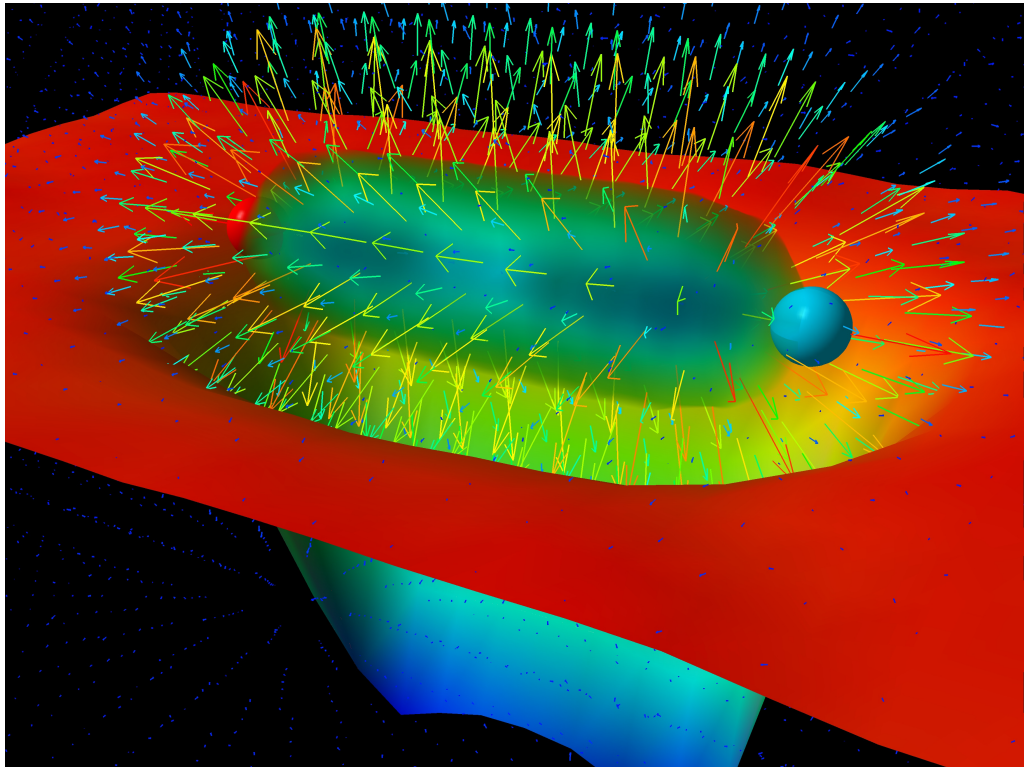
Federica Surace

Caltech

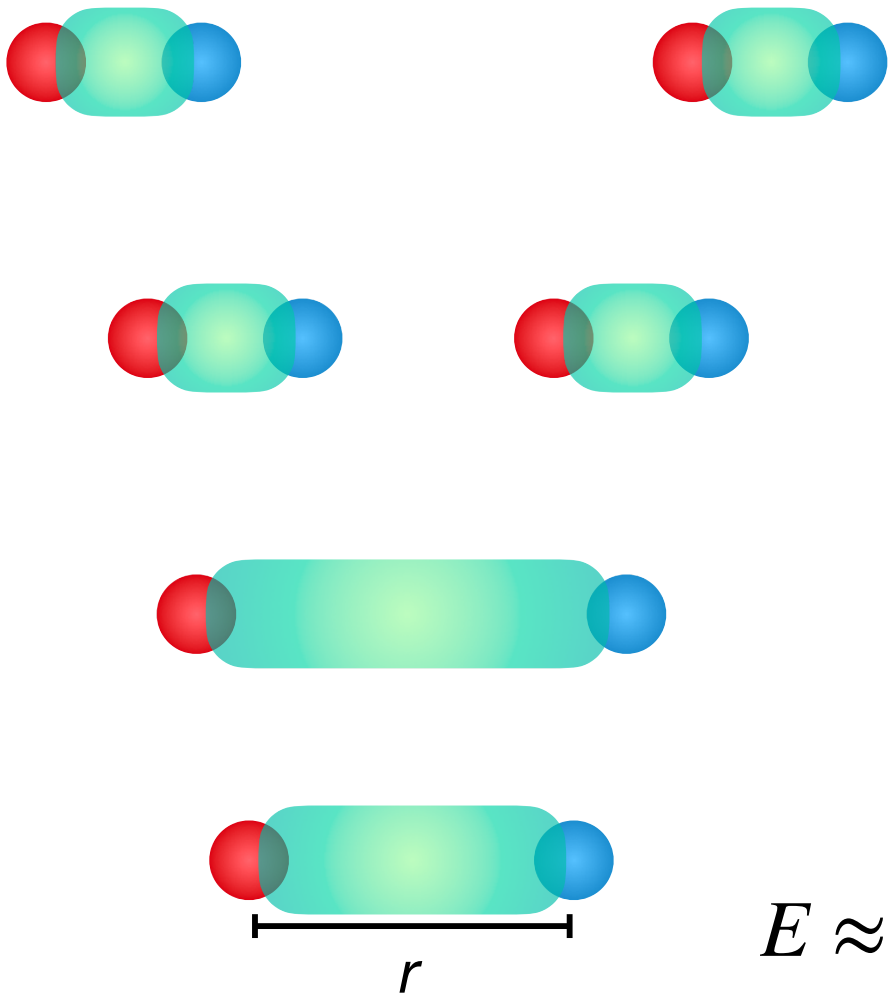


Energy → $E \approx \sigma r$ ← Distance

String tension

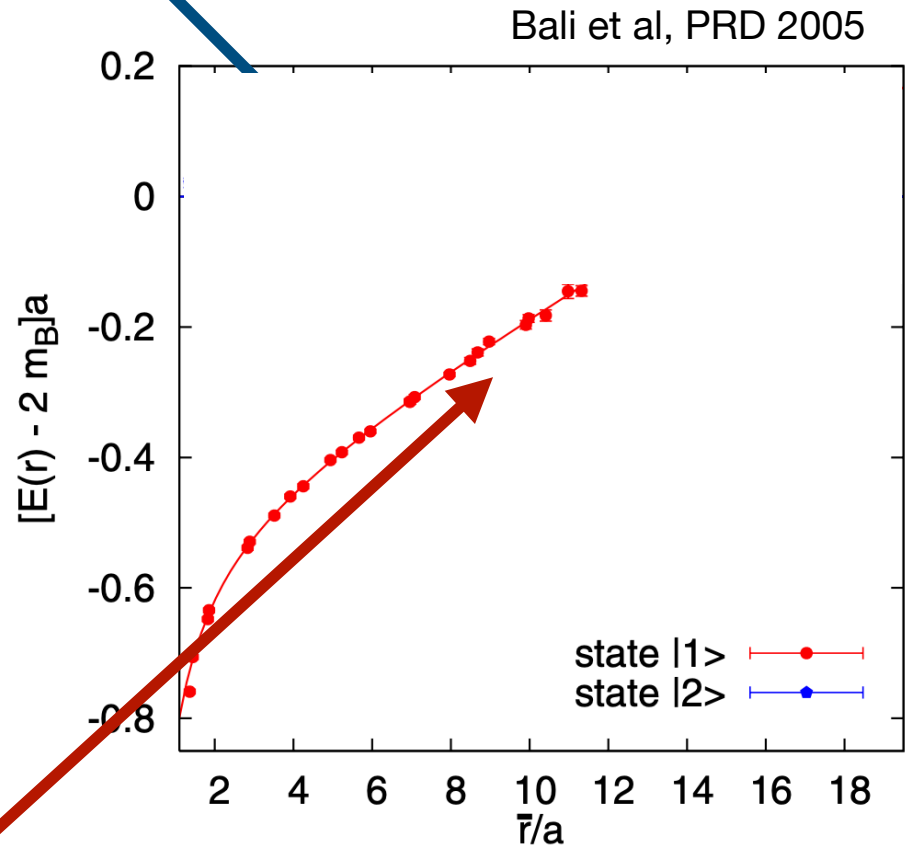


Credits: Derek Leinweber



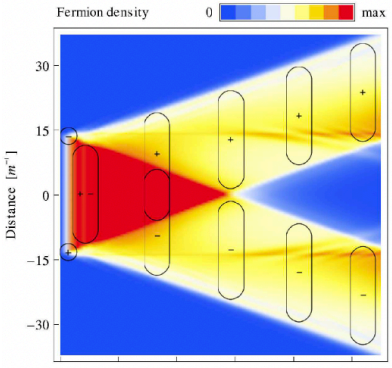
$E \approx 2M$

$E \approx \sigma r$

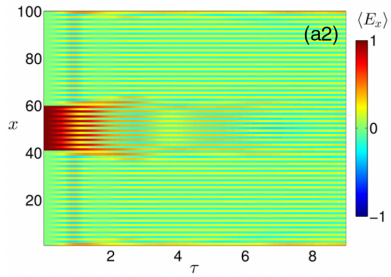


String breaking

Schwinger model

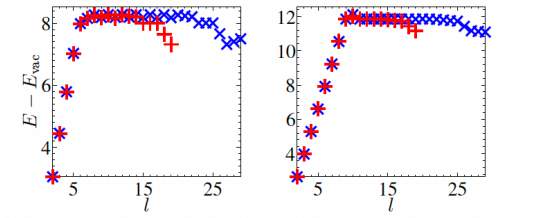


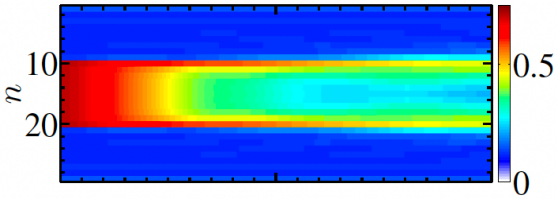
Hebenstreit, Berges, Gelfand,
PRL 2013



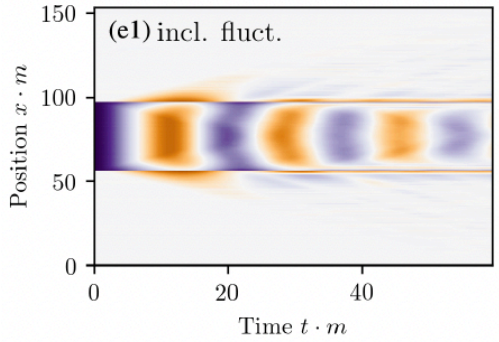
Pichler, Dalmonte, Rico, Zoller,
Montangero, PRX 2016

Non-Abelian LGTs



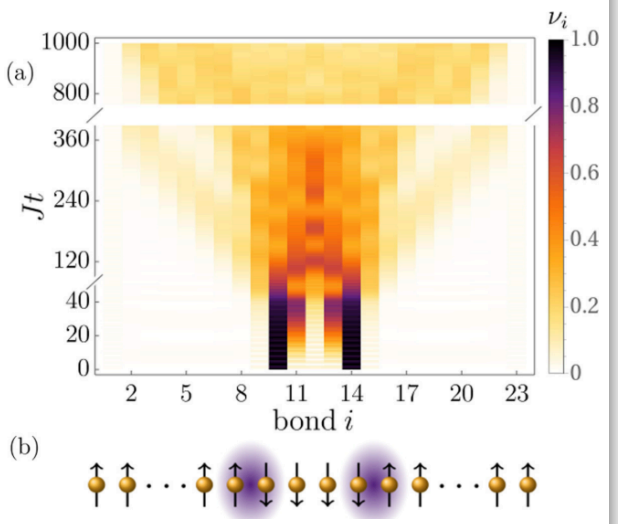


Kuhn, Zohar, Cirac, Banuls,
JHEP 2015



Spitz Berges, PRD 2019

Ising model



Verdel, Liu, Whitsitt, Gorshkov,
Heyl, PRB 2020
Verdel, Zhu, Heyl, PRL 2023

… and this work!

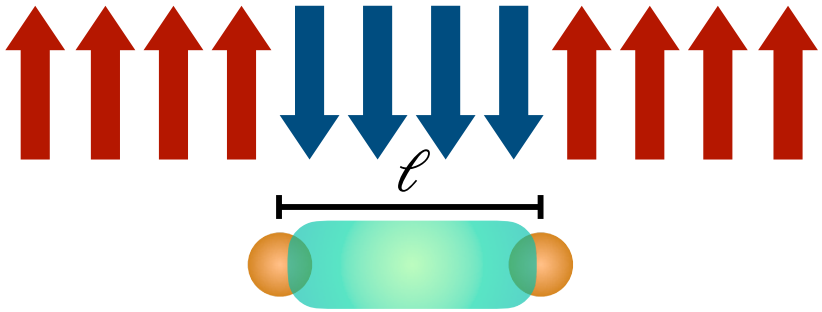
Ising chain: confinement

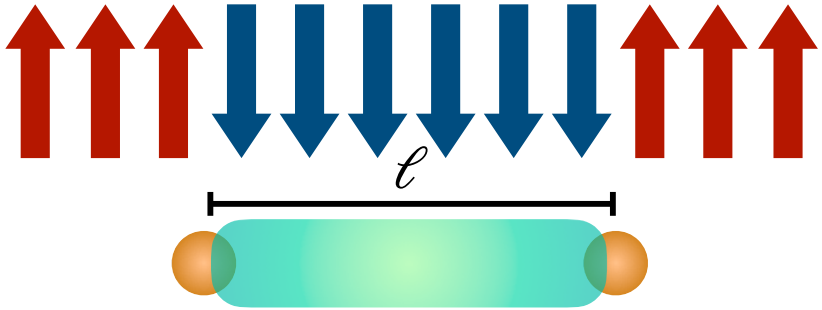
$$H = -\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z - g\sum_j \sigma_j^x - h\sum_j \sigma_j^z$$

g small

$$E(\ell) \approx 4J + 2h\ell$$

string tension



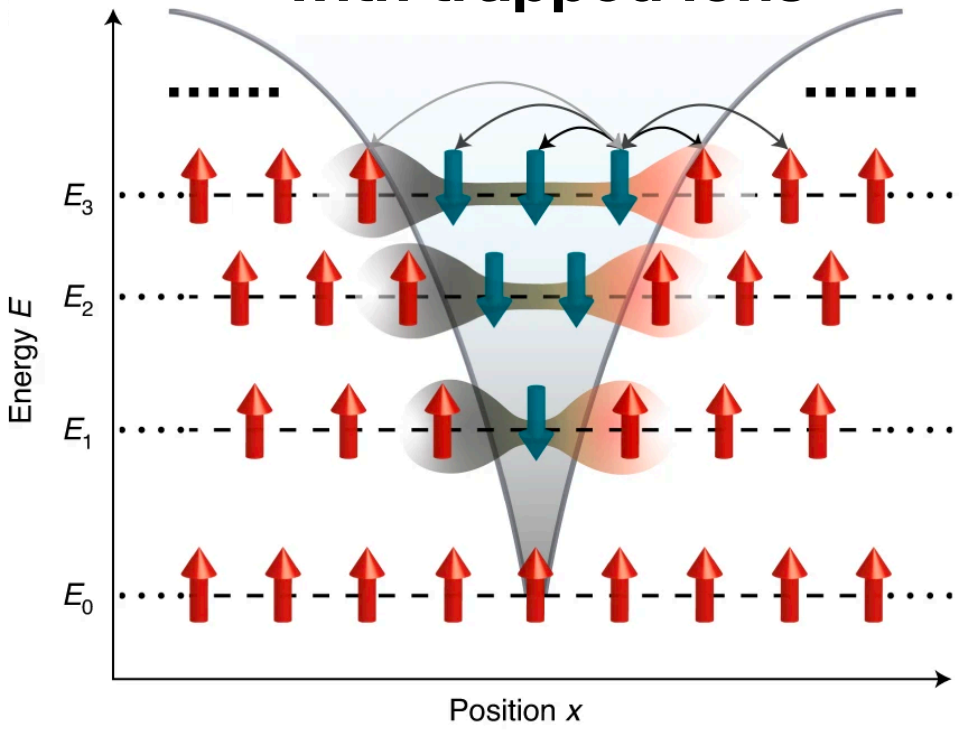


Ising chain: confinement

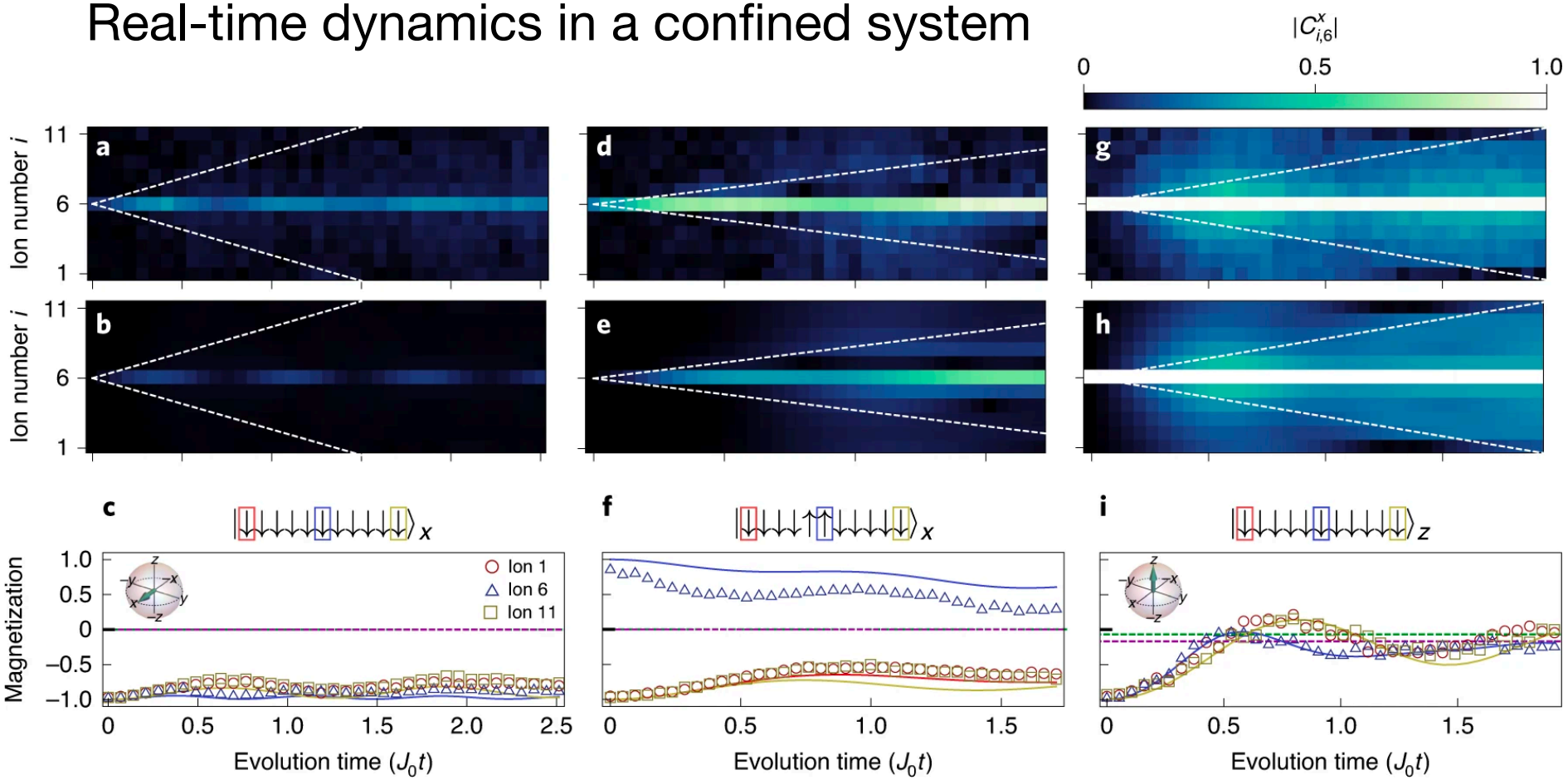
$$H = -\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z - g\sum_j \sigma_j^x - h\sum_j \sigma_j^z$$

Long range

Quantum simulation with trapped ions



Real-time dynamics in a confined system

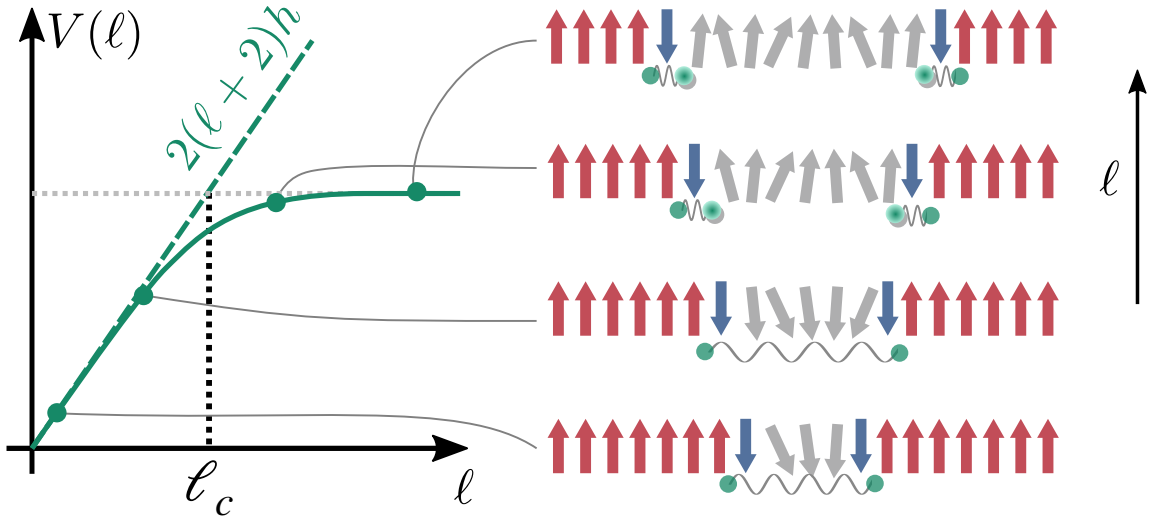


Tan, Becker, Liu, Pagano, Collins, De, Feng, Kaplan, Kyprianidis, Lundgren, Morong, Whitsitt, Gorshkov, Monroe, Nat. Phys. 2021

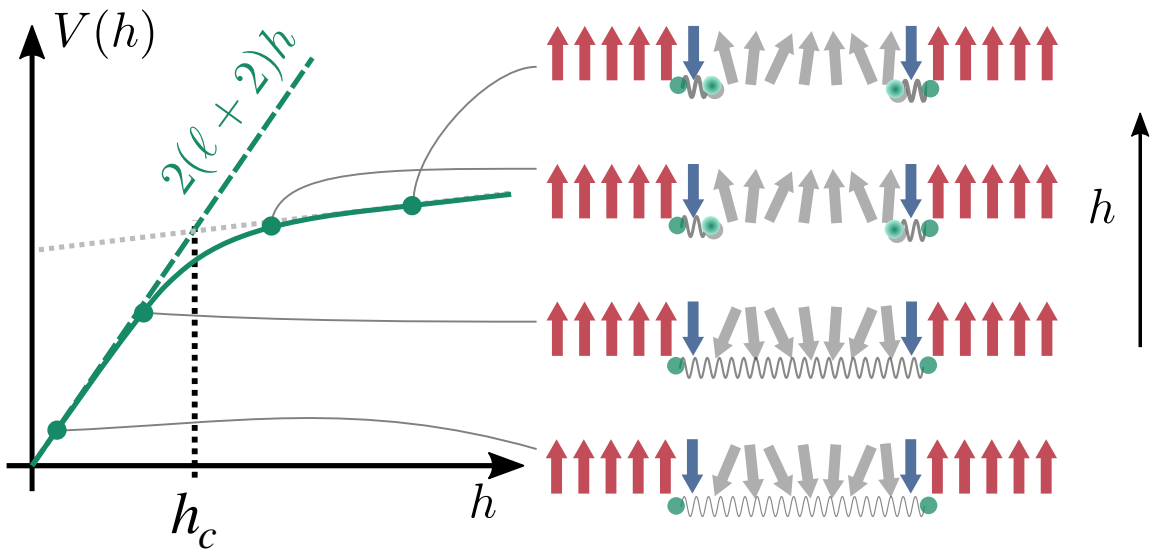
Confinement *demonstrated in trapped ions* ✔

…can one observe ***string breaking****?*

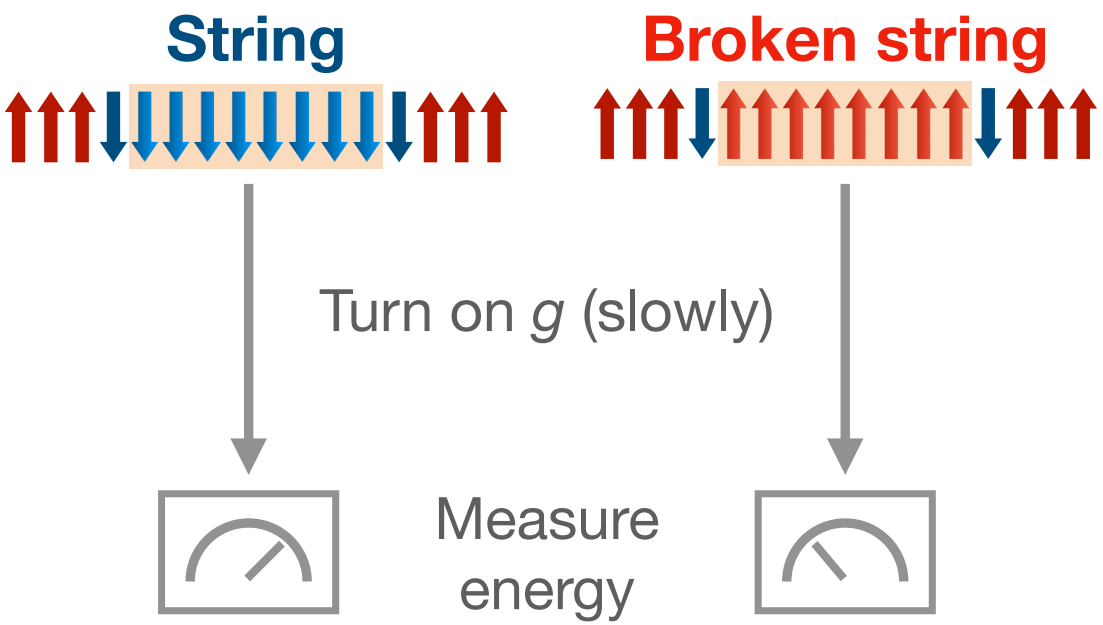
Constant h:
string breaks at ℓ_c

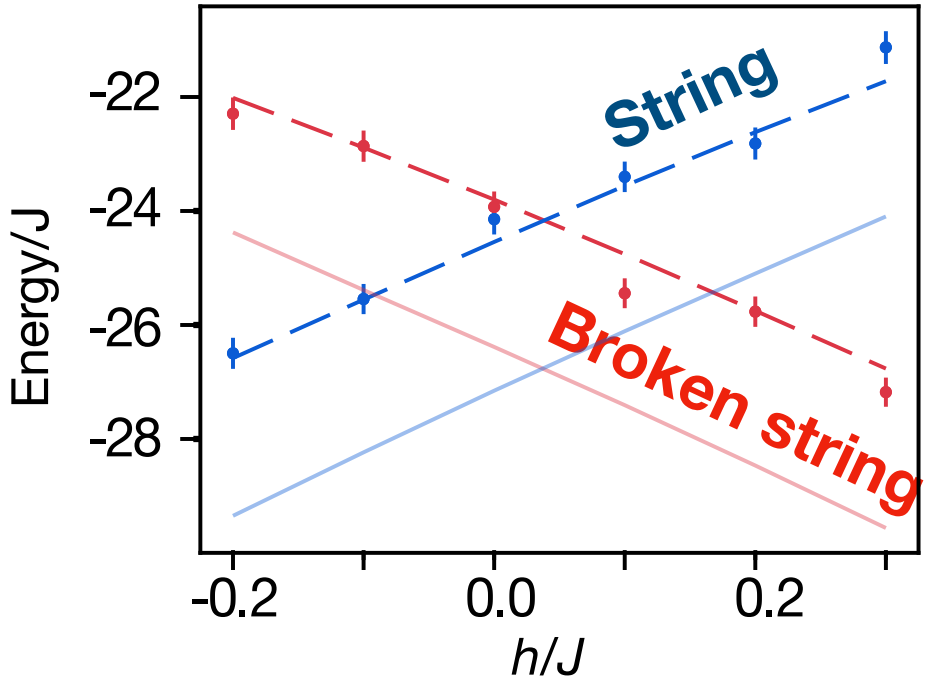


Constant ℓ:
string breaks at h_c

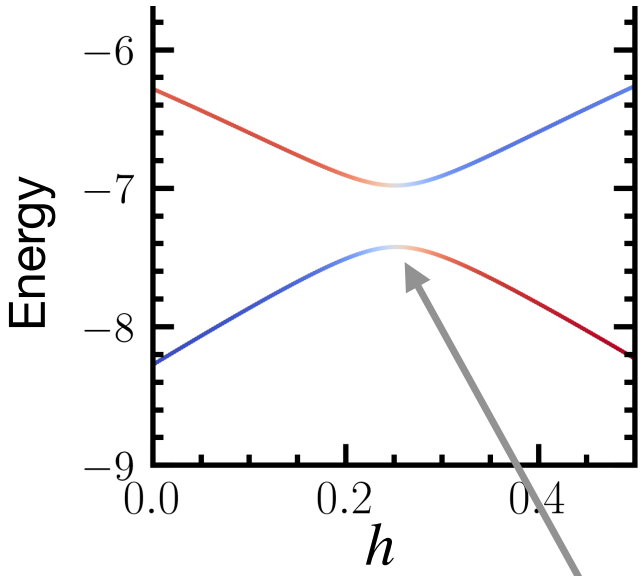


$$H = -\sum_{1\le i<j\le \ell} J_{ij}\sigma_i^z\sigma_j^z - g\sum_{j=1}^{\ell}\sigma_j^x + \sum_{j=1}^{\ell}(h_j^{\mathrm{eff}} - h)\sigma_j^z$$





Finding h_c



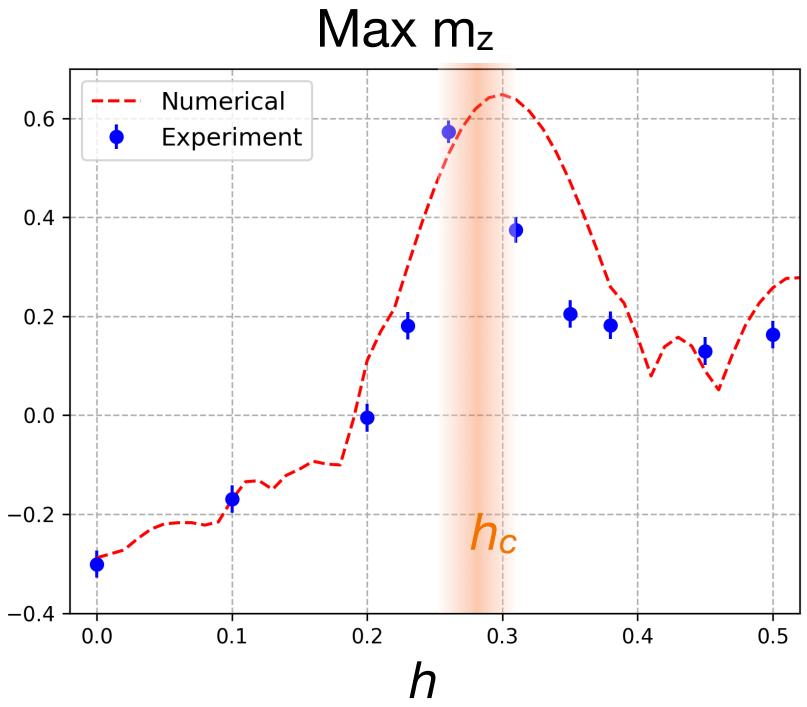
Quench $h = 0 \rightarrow h = h_c$

Oscillations between

 and

At the crossing: $|E_{\pm}\rangle \approx \frac{1}{\sqrt{2}}\left(\left| \downarrow\downarrow\downarrow\downarrow\downarrow \right\rangle \pm \left| \uparrow\uparrow\uparrow\uparrow\uparrow \right\rangle \right)$

Finding h_c



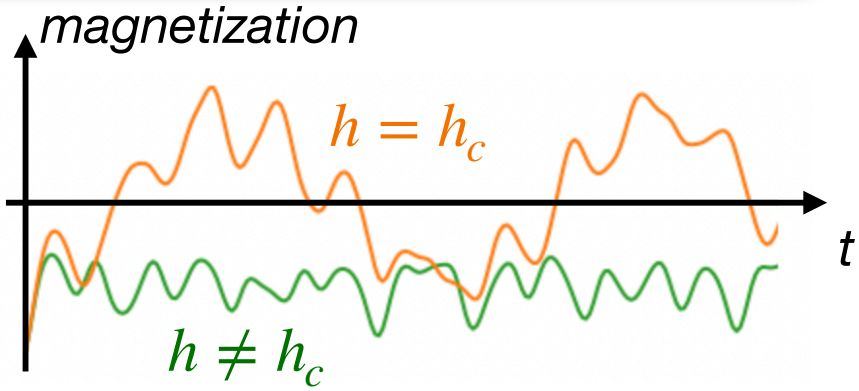
Challenging for longer strings:

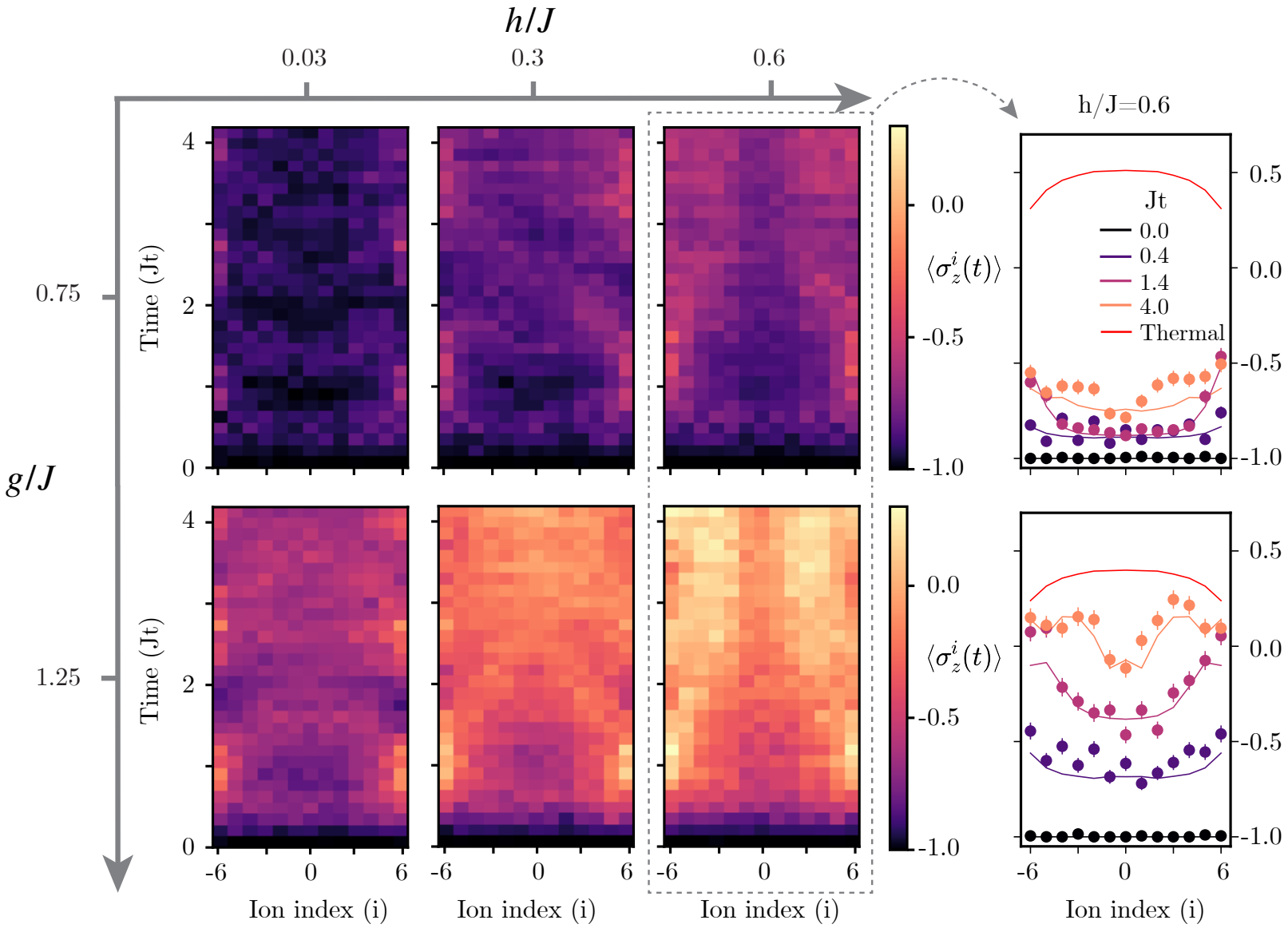
- narrow peak
- long times needed

Quench $h = 0 \rightarrow h = h_c$

Oscillations between

and



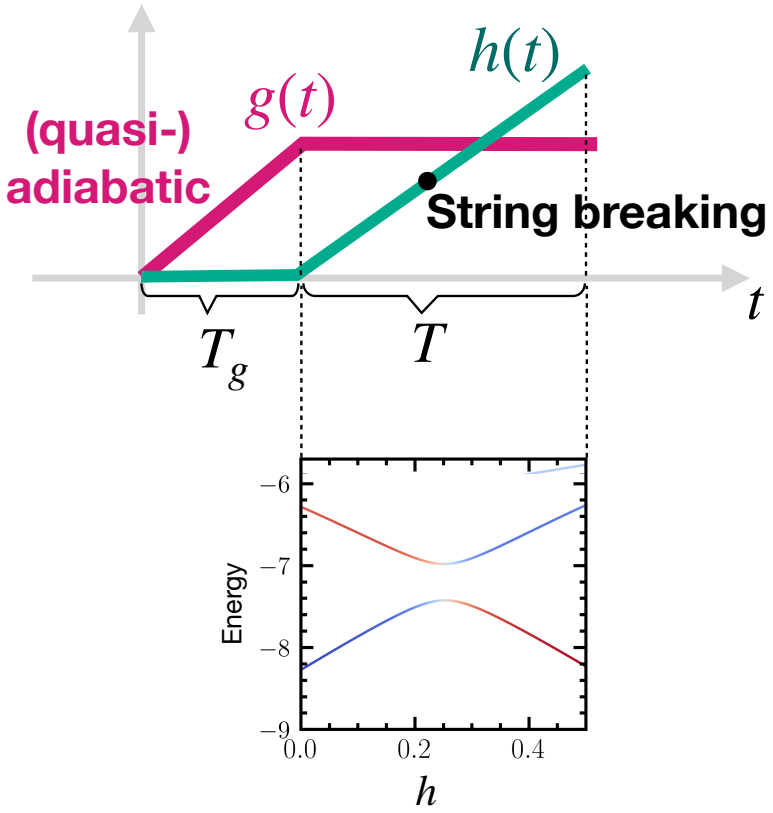


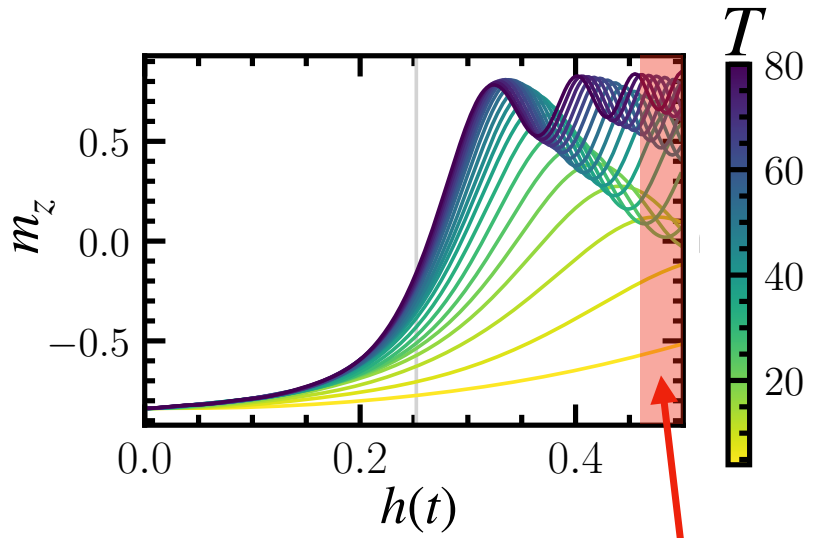
Quench

Slow thermalization

Ramp

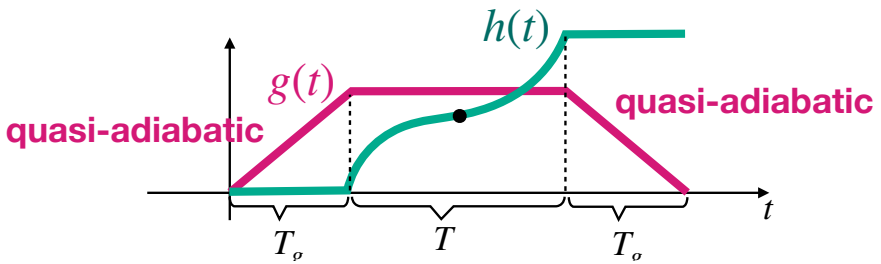
$$H = -\sum_{1\le i<j\le \ell} J_{ij}\sigma_i^z\sigma_j^z - g\sum_{j=1}^{\ell}\sigma_j^x + \sum_{j=1}^{\ell}(h_j^{\text{eff}} - h)\sigma_j^z$$

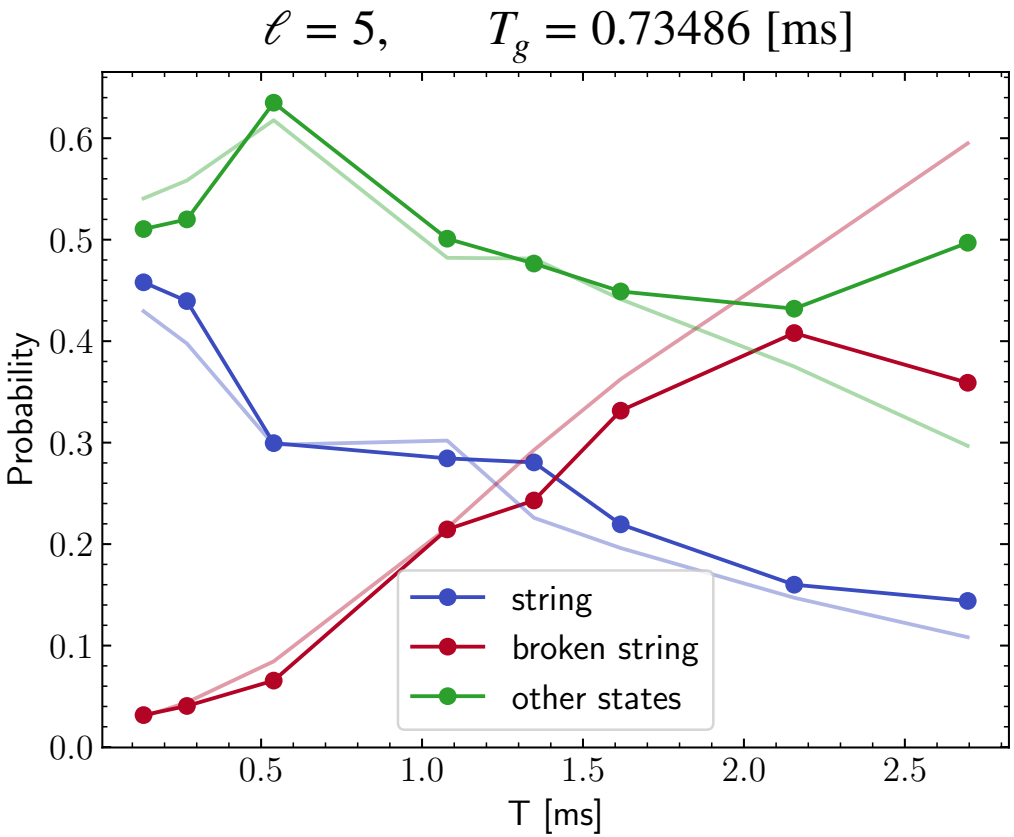


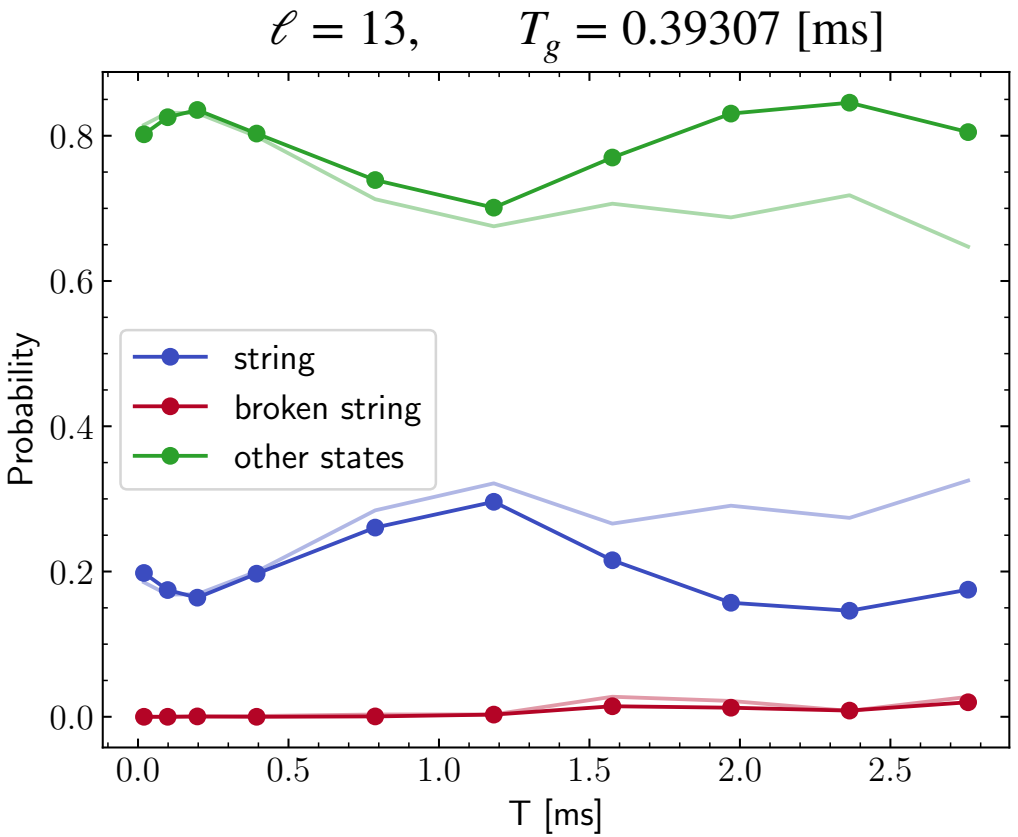


~ Landau Zener

Double ramp


h(t)
g(t)
quasi-adiabatic
quasi-adiabatic
t
T_g
T
T_g


$\ell = 5, \quad T_g = 0.73486$ [ms]
Probability
T [ms]
string
broken string
other states


$\ell = 13, \quad T_g = 0.39307$ [ms]
Probability
T [ms]
string
broken string
other states

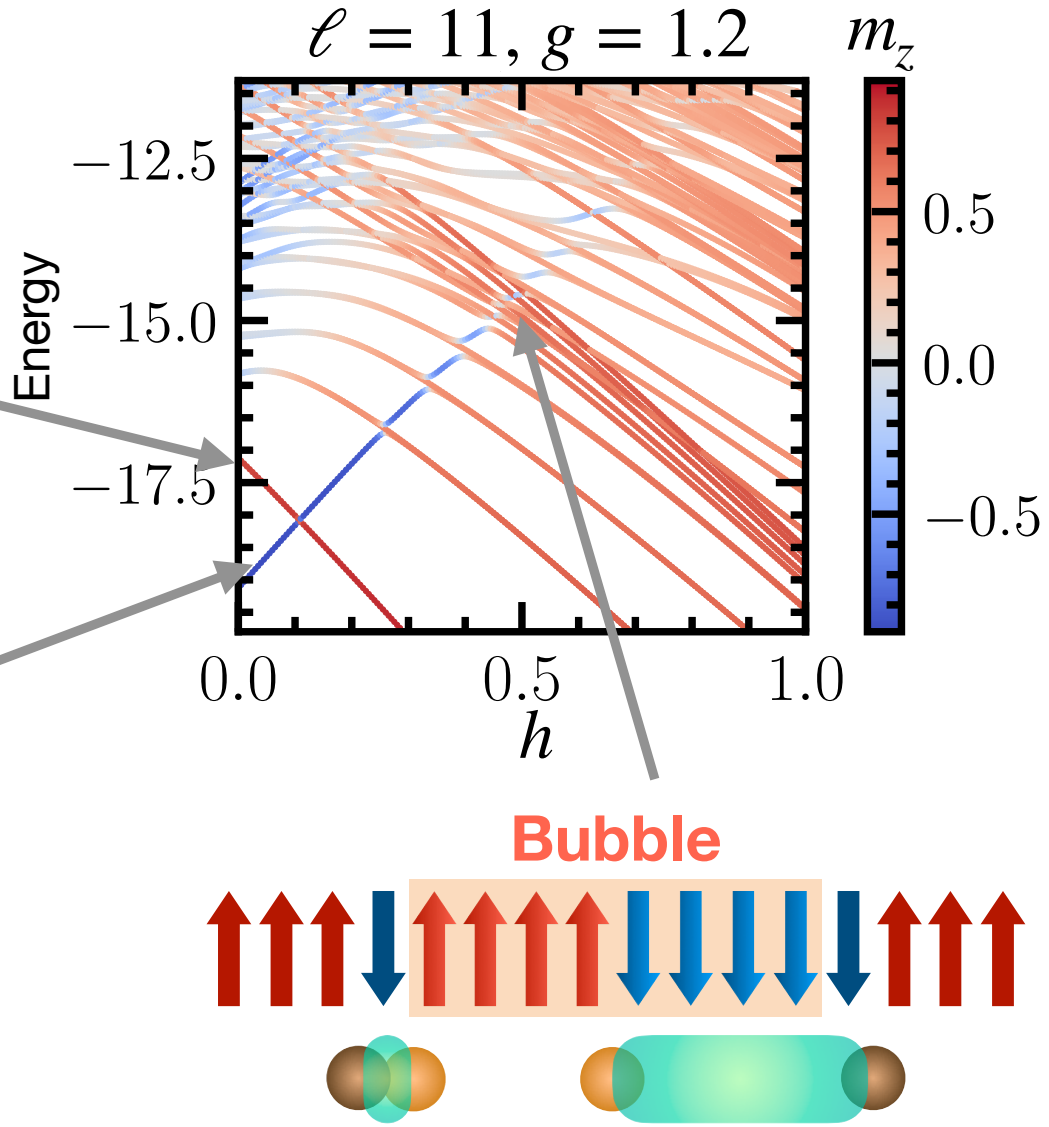
For long strings:

the gap is too small

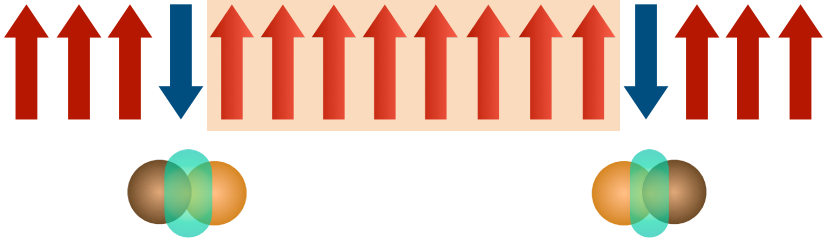
The evolution is always diabatic

Can the string break in this case?

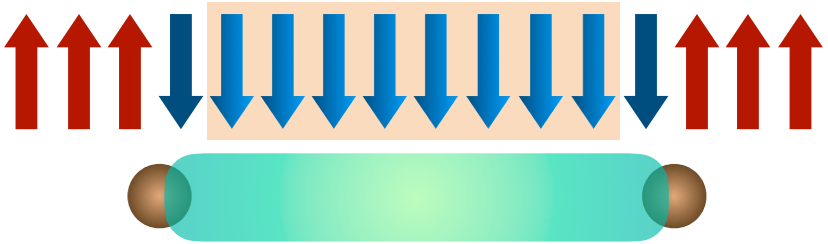
Beyond h_c



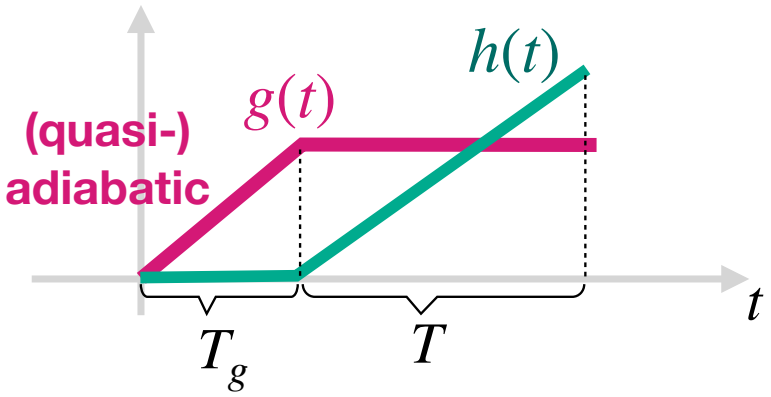
Broken string



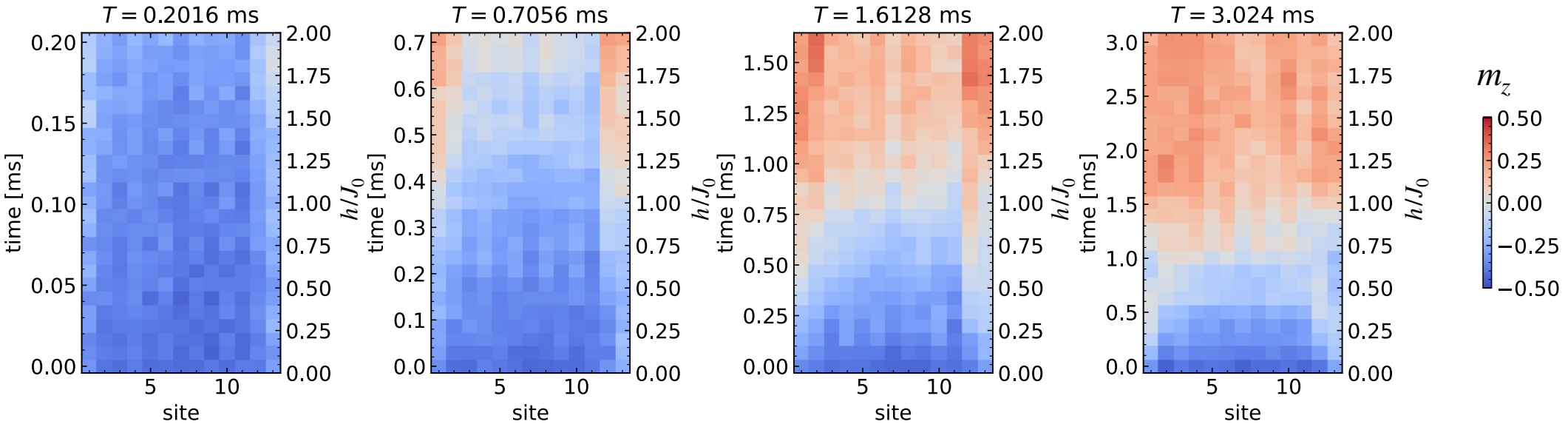
String



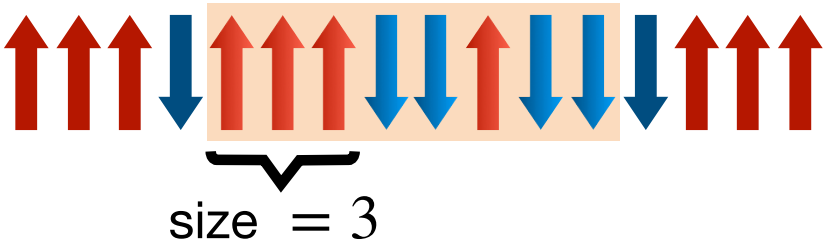
Bubble



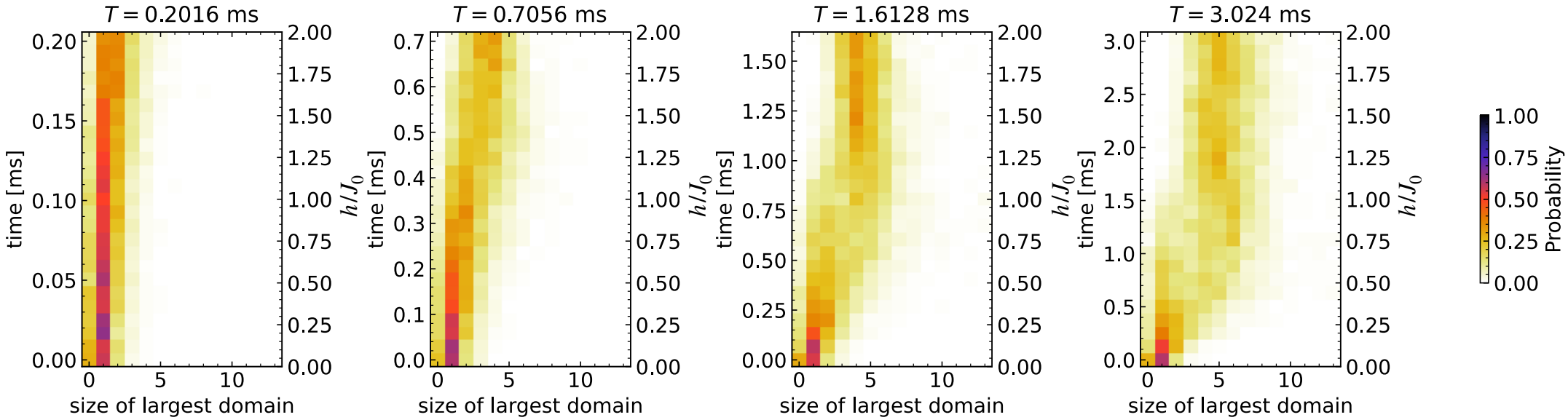
slower = breaks at smaller h



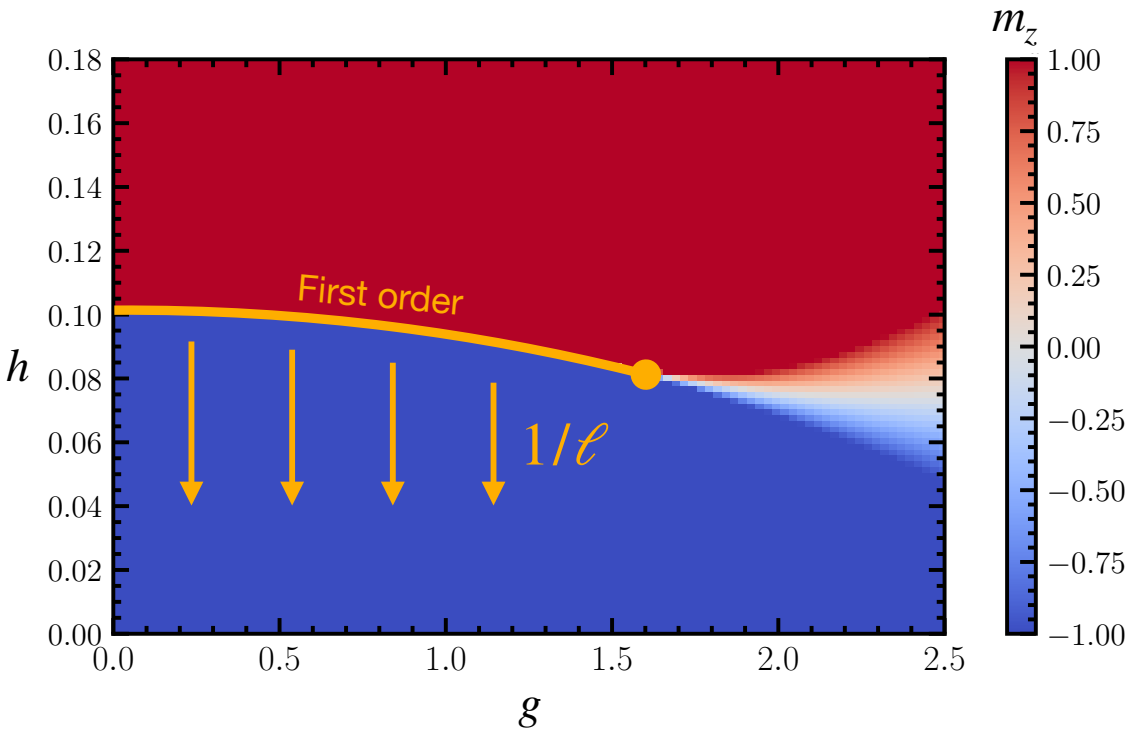
Size of largest ↑ domain (bubble)



slower = larger bubbles



String breaking as a false vacuum decay



Lagnese, **FMS**, Calabrese, PRB 2021

Lagnese, **FMS**, Morampudi, Wilczek, arXiv:2308.08340

Yin, **FMS**, Lucas, arXiv:2408.05261

Sinha, Chanda, Dziarmaga, PRB 2021

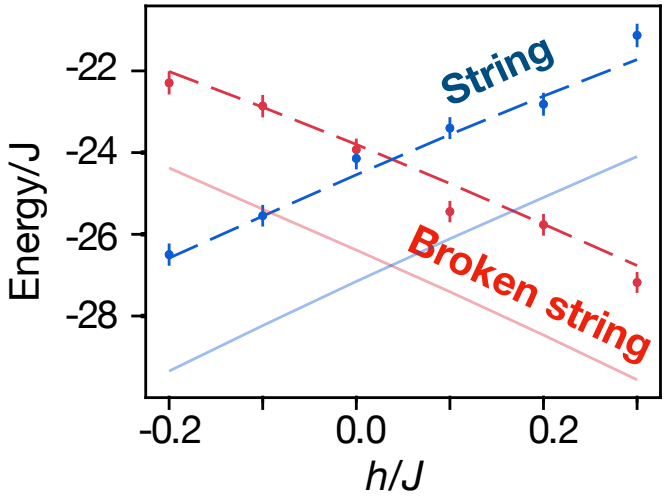
A. Zenesini, A. Berti, et al., Nat. Phys. 2024

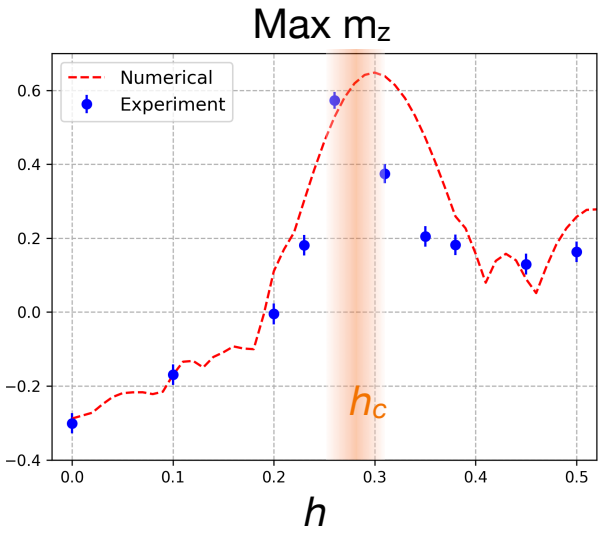
S. Darbha, M. Kornjača, et al., arXiv:2404.12360, arXiv:2404.12371

J. Vodeb, J. Desaules, et al., arXiv:2406.14718

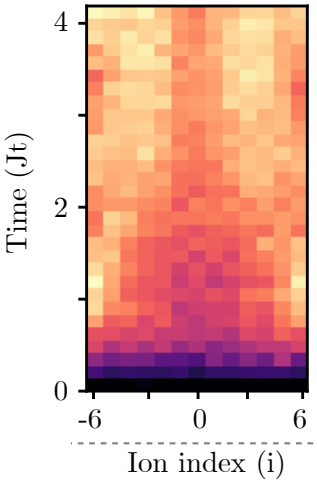
Summary

1. String breaking in trapped ion quantum simulator

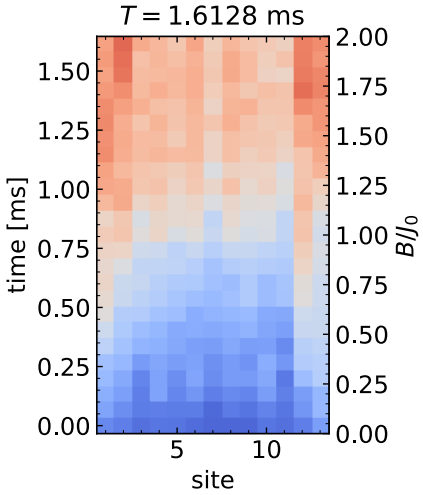




2. Protocol for finding the string breaking point



3. Quench dynamics



4. Ramp dynamics

Theory

Alessio Lerose
Oxford

Elizabeth Bennewitz
UMD

Alex Schuckert
UMD

Brayden Ware
UMD

Alexey Gorshkov
UMD

Zohreh Davoudi
UMD

Experiment

(Henry) De Luo
Duke

Arinjoy De
JQI

Or Katz
Duke

Chris Monroe
JQI, Duke

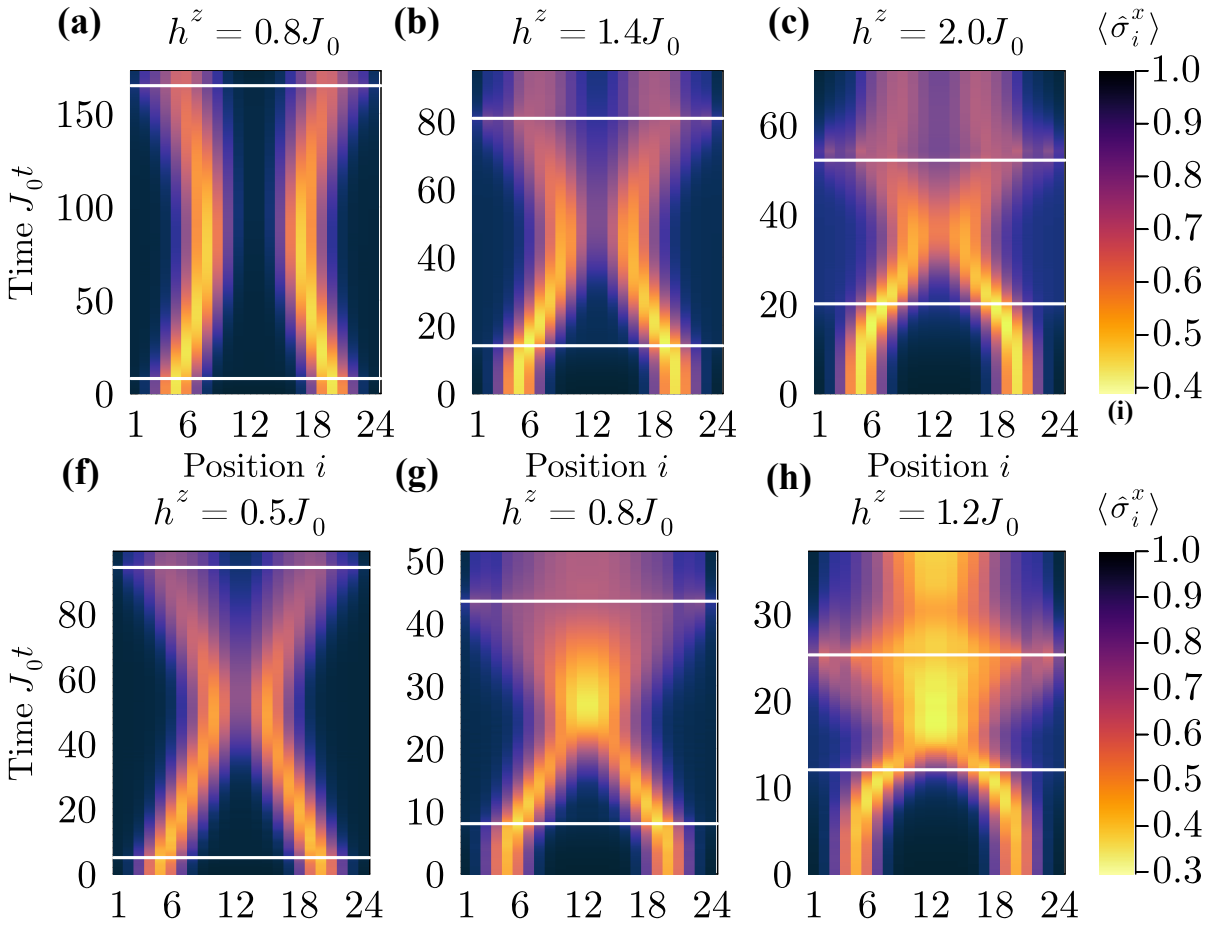
Kate Collins, William Morong

Meson scattering in trapped ion simulator

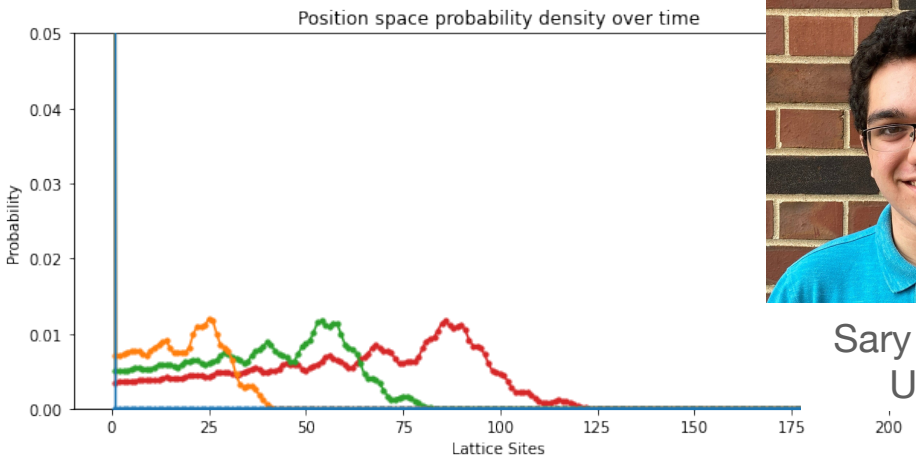
arxiv:2403.07061

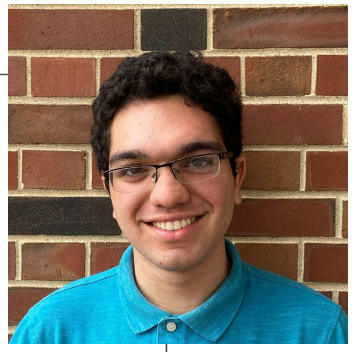
Elizabeth Bennewitz, UMD

E. Bennewitz, B. Ware,
A. Schuckert, A. Lerose,
FMS, R. Belyansky,
W. Morong, D. Luo, A. De,
K. Collins, O. Katz,
C. Monroe, Z. Davoudi,
A. Gorshkov



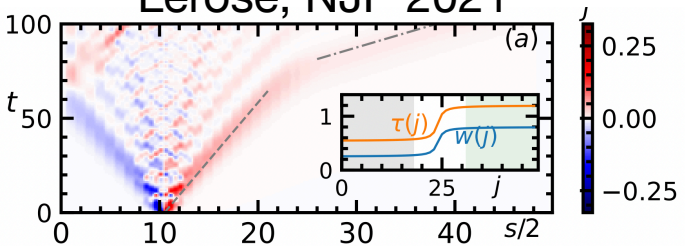
Quantum simulation of scattering

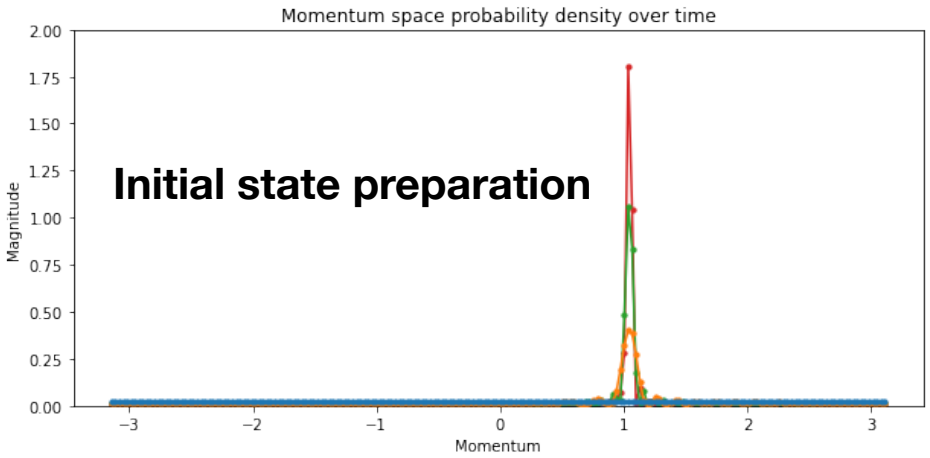




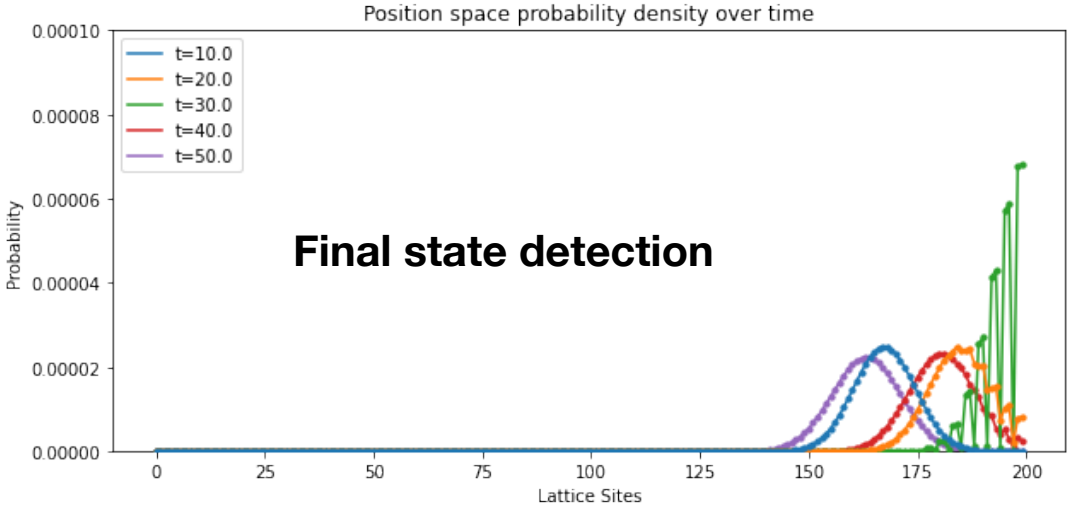
Sary Bseiso
UIUC

Similar protocol in FMS,
Lerose, NJP 2021





Initial state preparation



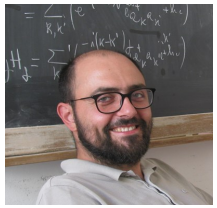
Final state detection

U(1) LGT with ultra cold atoms

PRX Quantum 4, 020330 (2023)

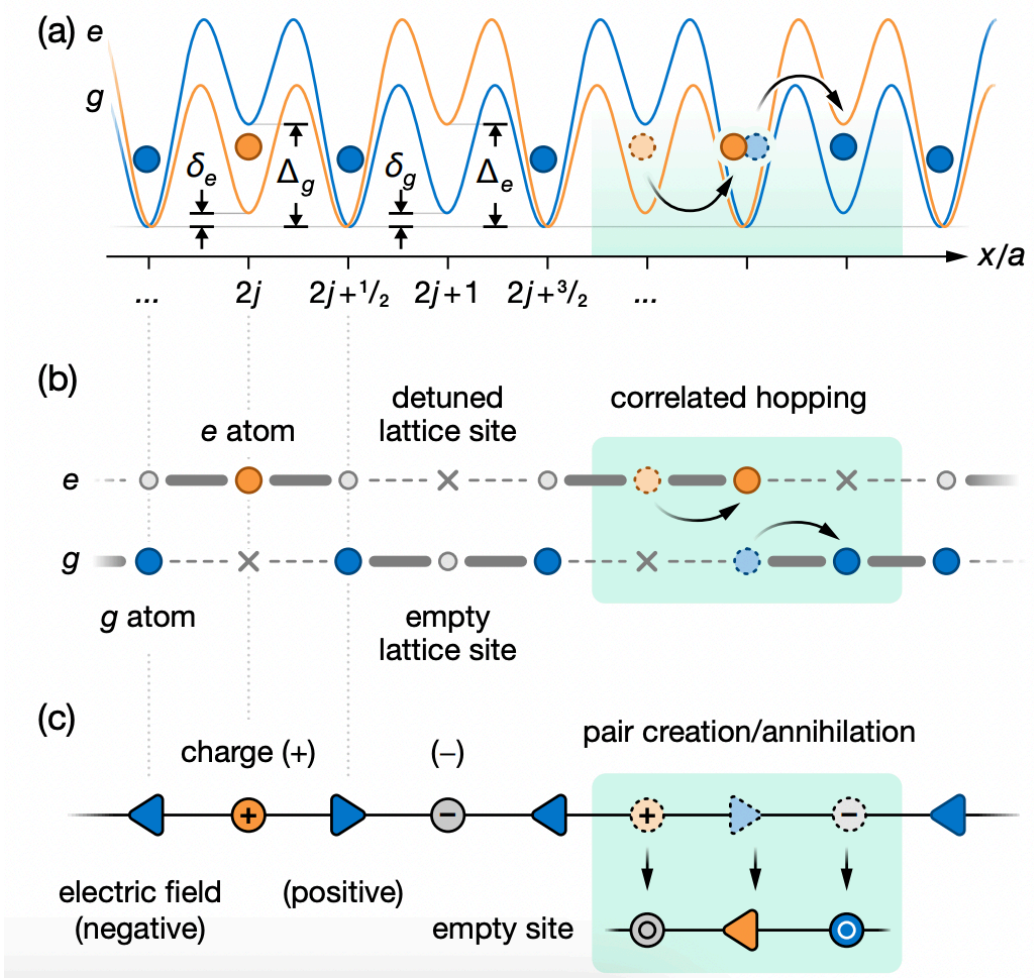
P. Fromholz

N. Darkwah Oppong

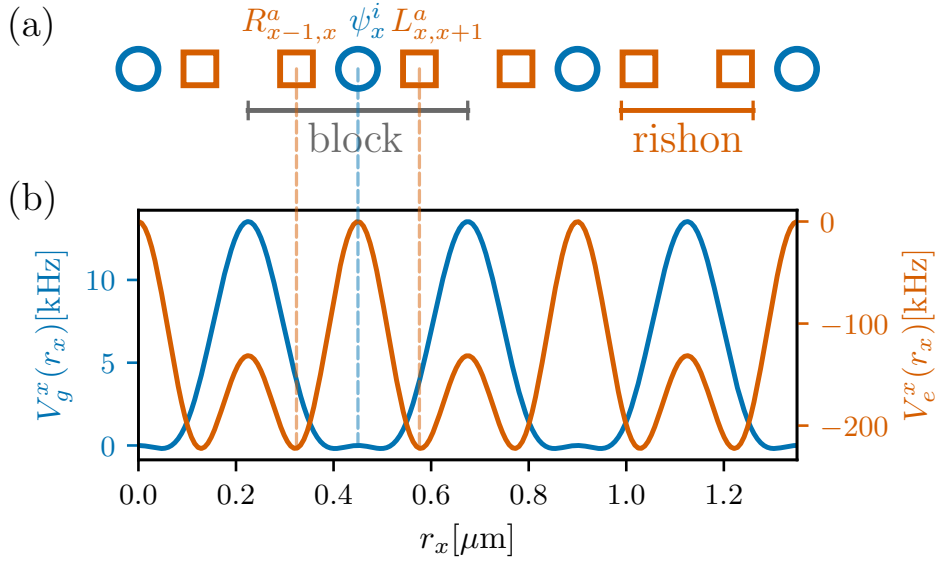


M. Dalmonte

M. Aidelsburger

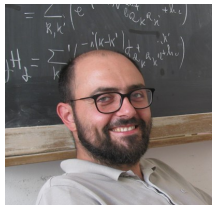


SU(N)xU(1) LGT with ultra cold atoms

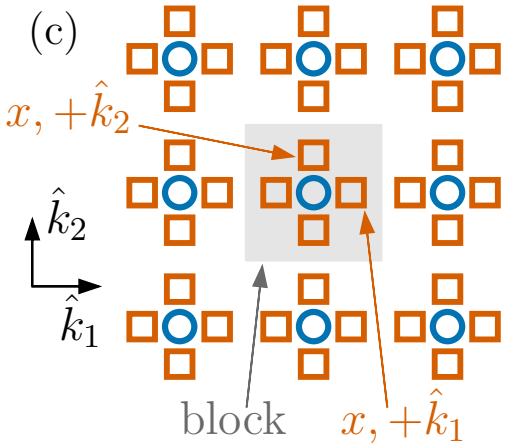


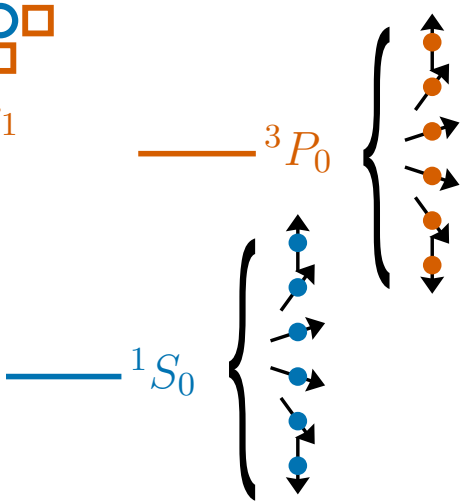
P. Fromholz

F. Scazza



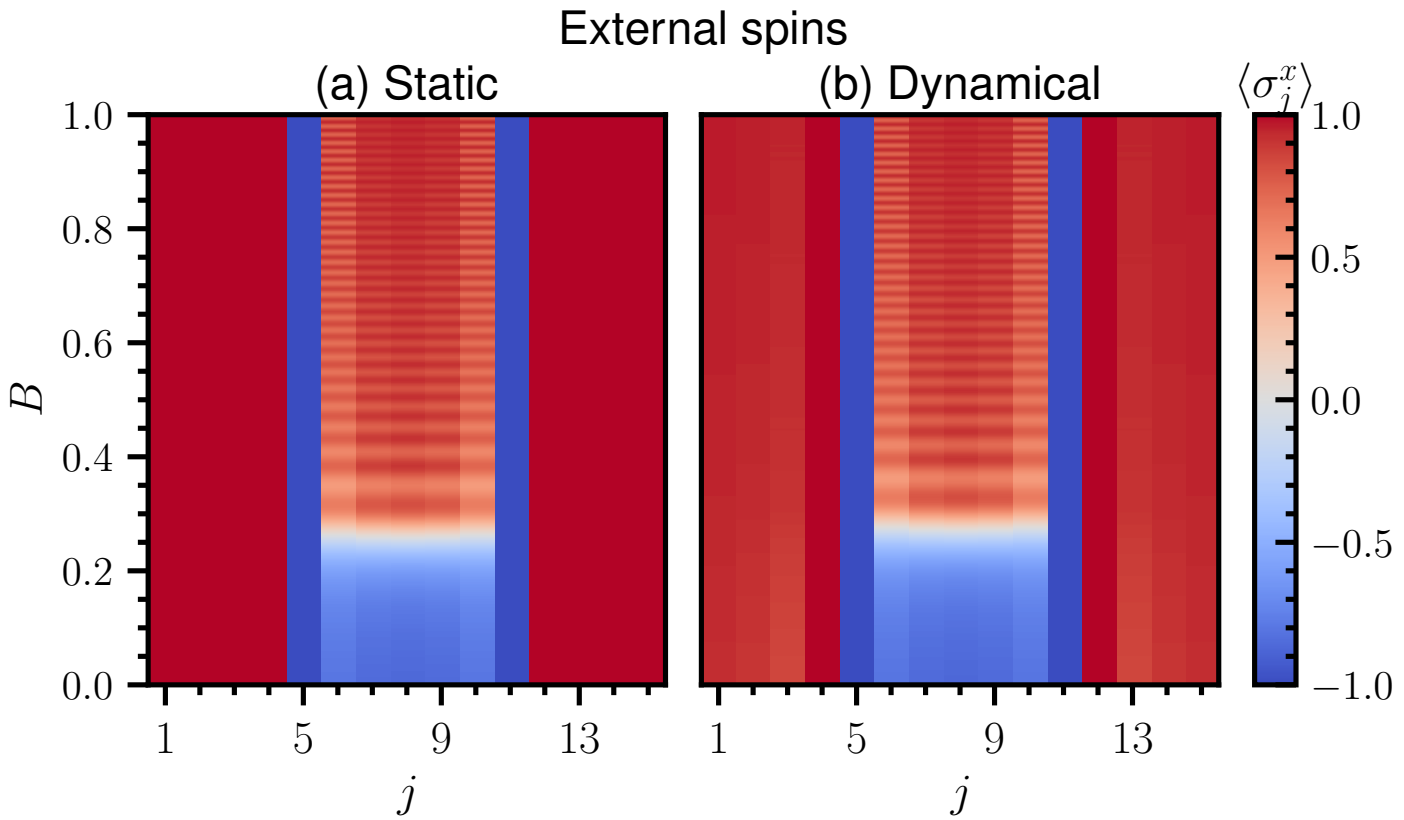
M. Dalmonte

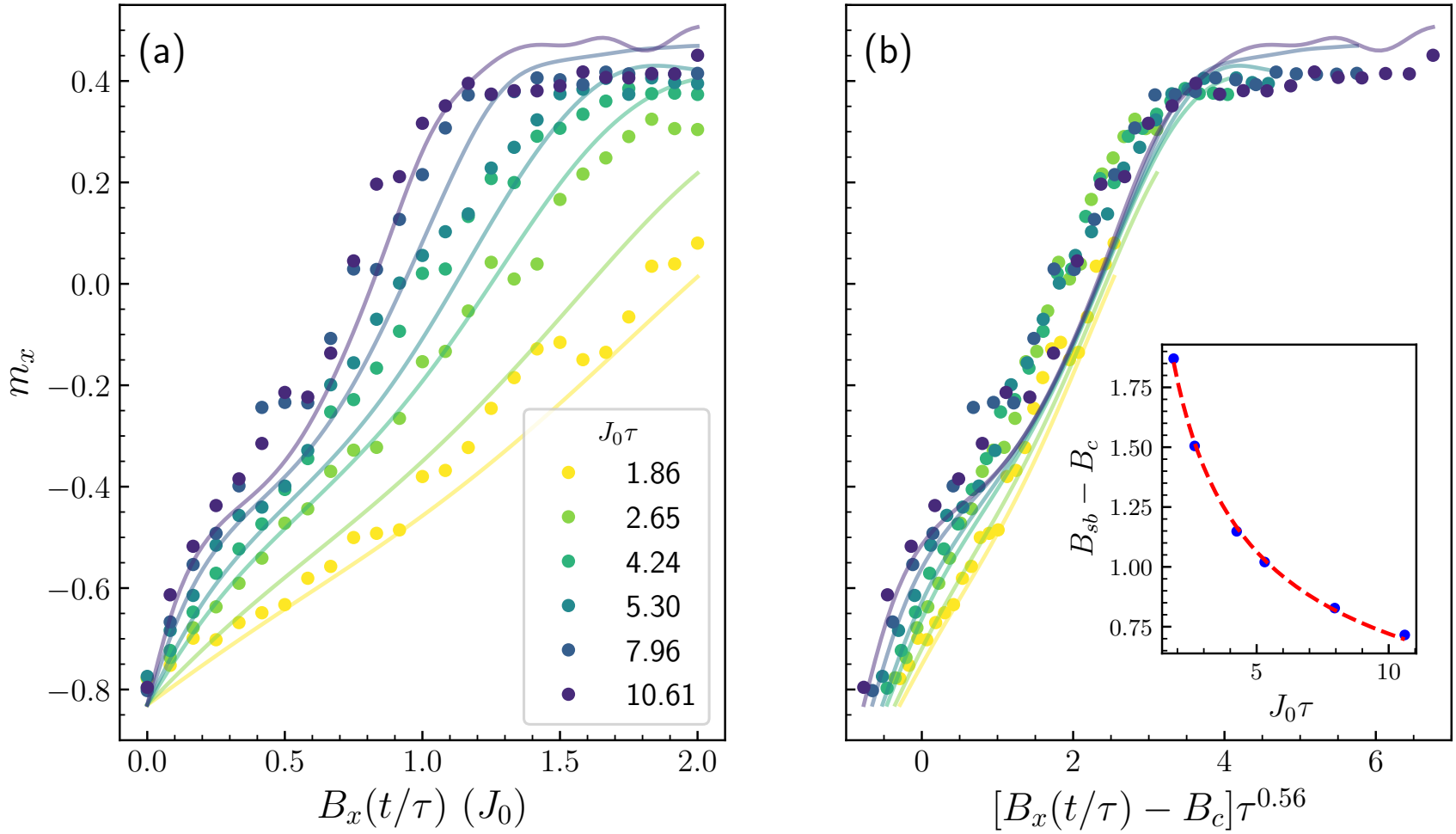




arXiv:2310.08643,
Quantum 2024

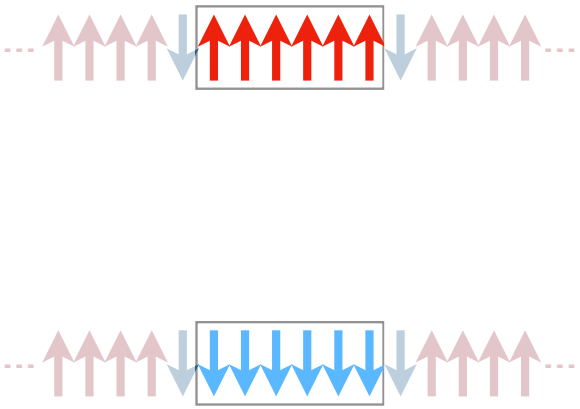
Thank you for your attention!

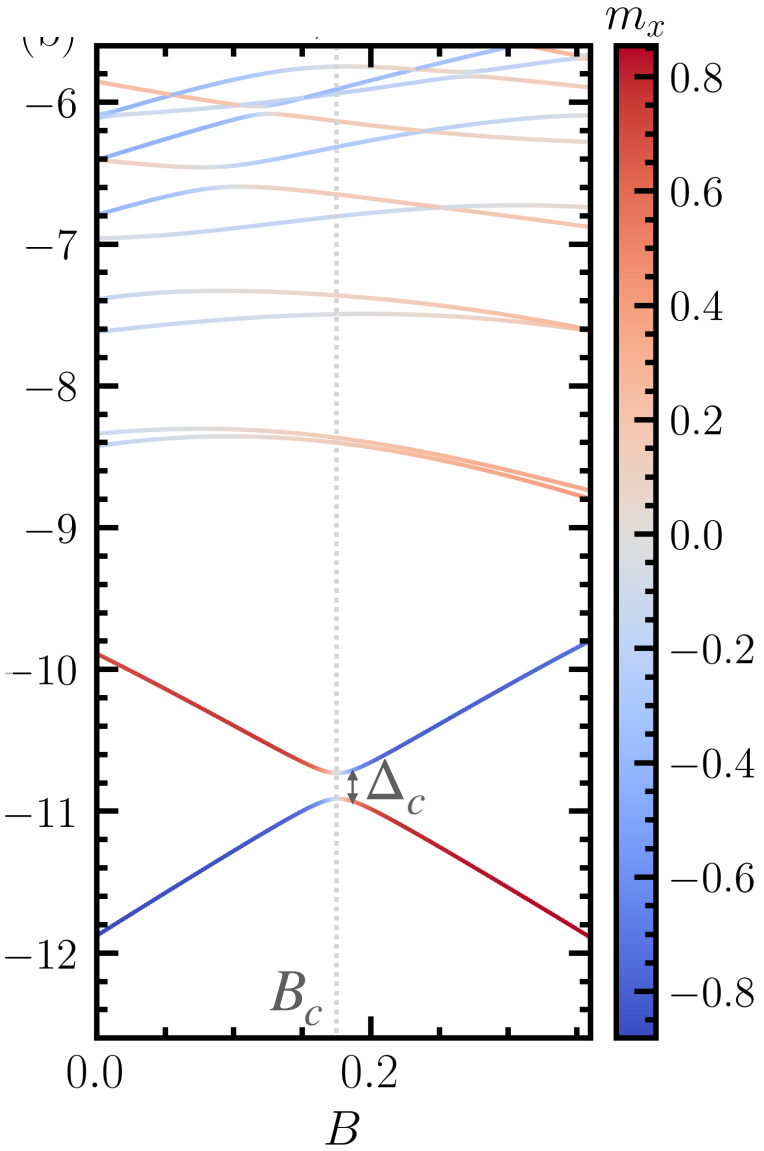

External spins
(a) Static
(b) Dynamical
$\langle \sigma_j^x \rangle$
1.0
0.5
0.0
−0.5
−1.0
B
0.0
0.2
0.4
0.6
0.8
1.0
1
5
9
13
j

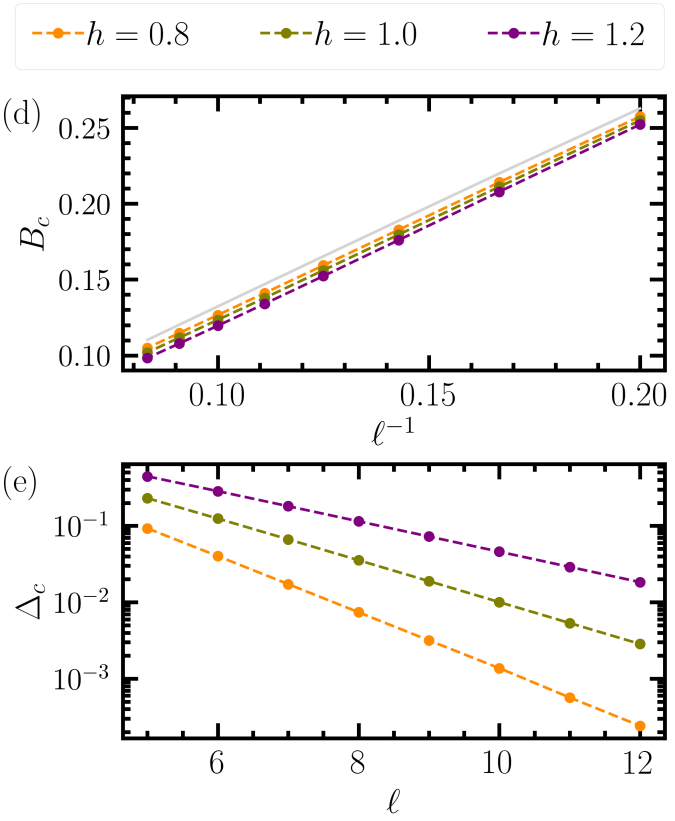

(a)
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
m_x
0.0
0.5
1.0
1.5
2.0
$B_x(t/\tau)$ (J_0)
$J_0\tau$
1.86
2.65
4.24
5.30
7.96
10.61
(b)
0
2
4
6
$[B_x(t/\tau) - B_c]\tau^{0.56}$
1.75
1.50
1.25
1.00
0.75
$B_{sb} - B_c$
5
10
$J_0\tau$

Spectrum

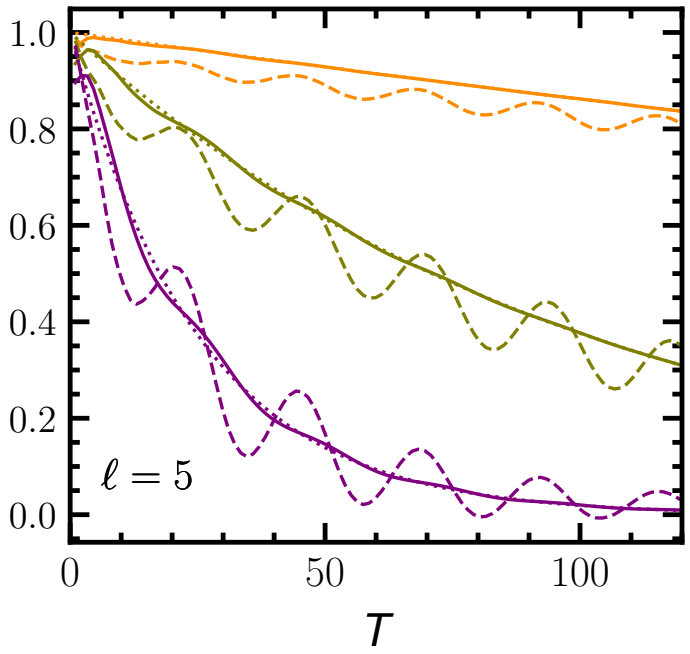
$$H = -\sum_{1\le i<j\le \ell} J_{ij}\sigma_i^x\sigma_j^x - h\sum_{j=1}^{\ell}\sigma_j^z + \sum_{j=1}^{\ell}(B_j^{\text{eff}} - B)\sigma_j^x$$

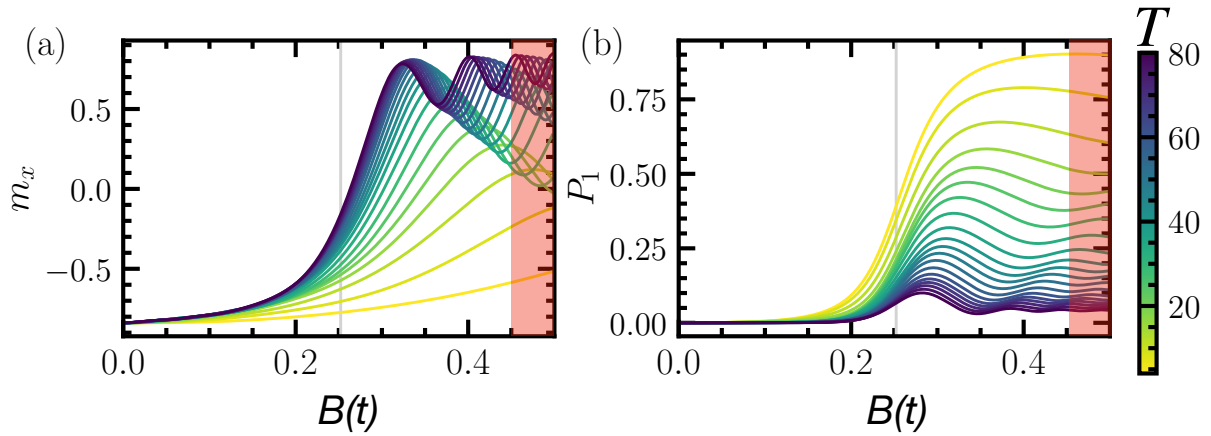






Landau-Zener





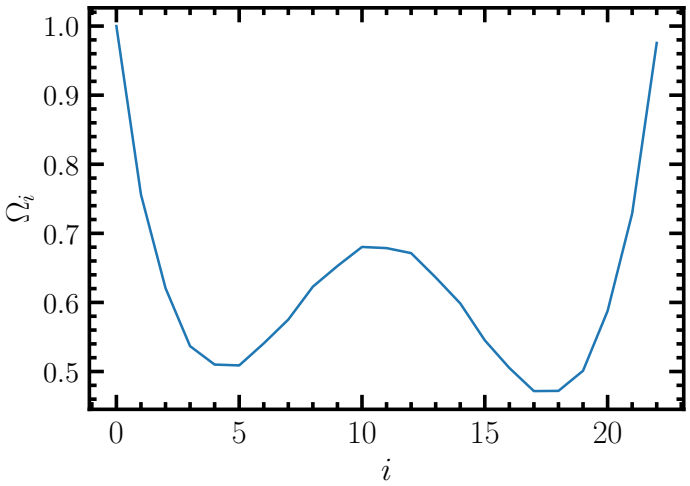
$h = 0.8$
$h = 1.0$
$h = 1.2$
P_1
P_{LZ}
P_m

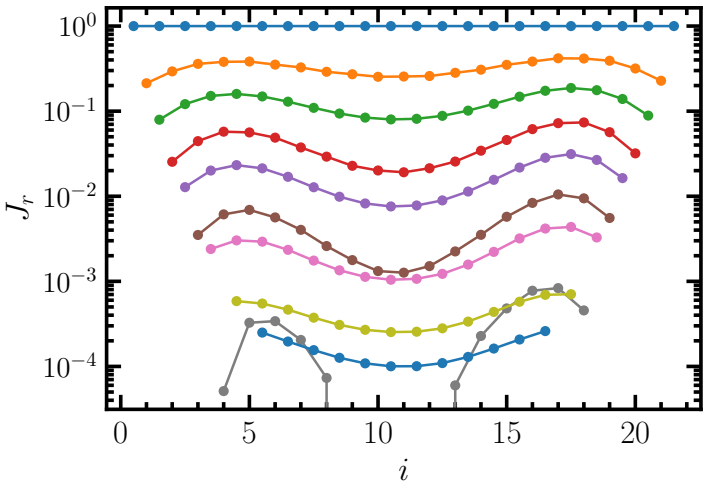
$$P_{\mathrm{LZ}} = \exp\left(-\frac{\pi \Delta_c^2 T}{4 \ell m_*}\right)$$

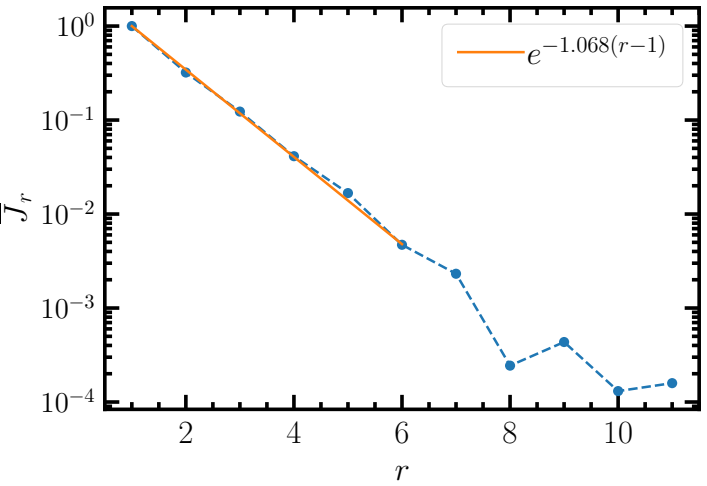
$$P_m = \frac{m_x^0 + m_x^{\mathrm{fin}}}{2 m_x^0}$$ (can be measured)

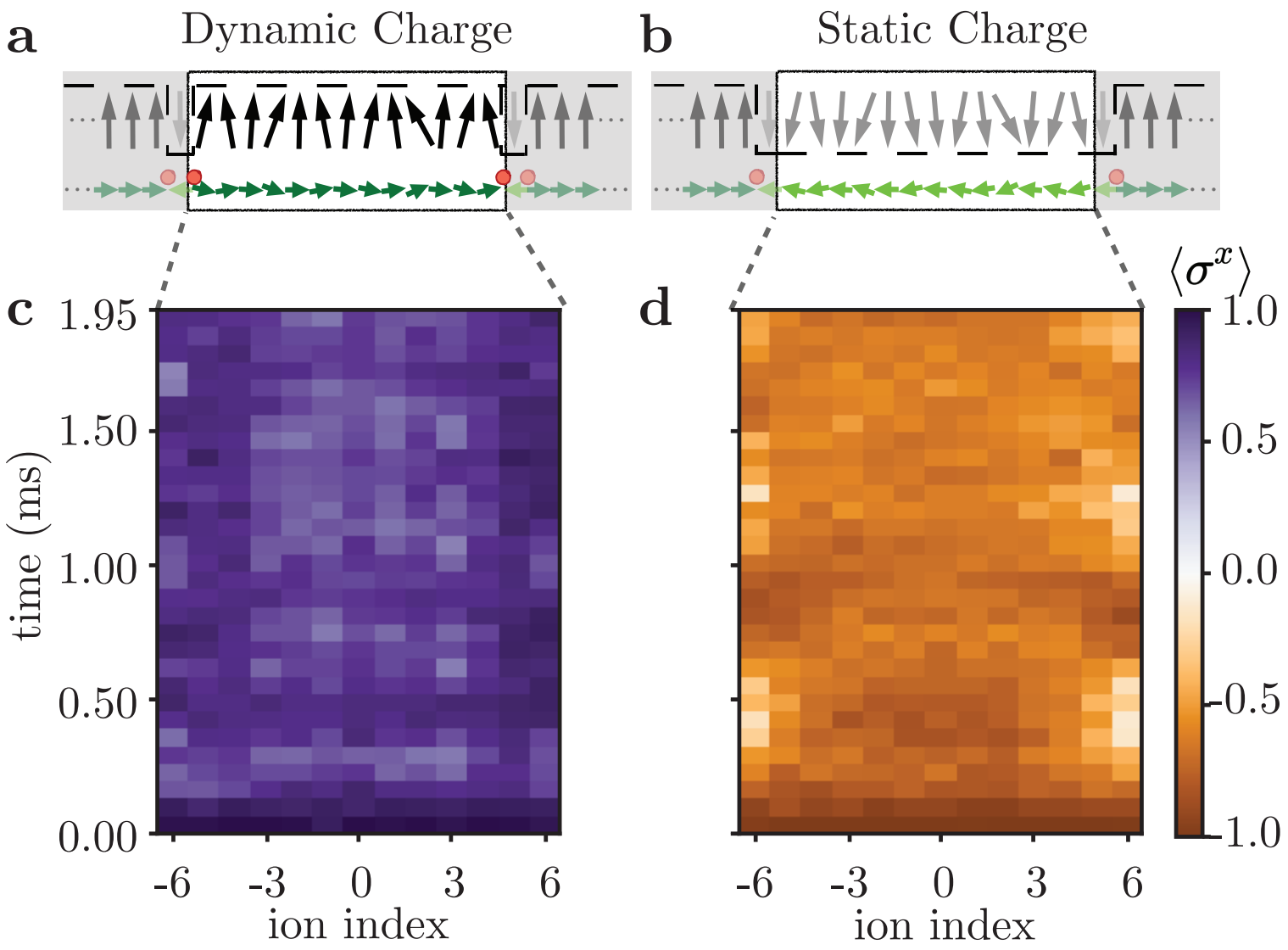
Experimental setup

$$J_{ij} = \sum_{k=1}^{N} \frac{\eta_i \eta_j \Omega_i \Omega_j}{\omega_N + \mu - \omega_k}$$

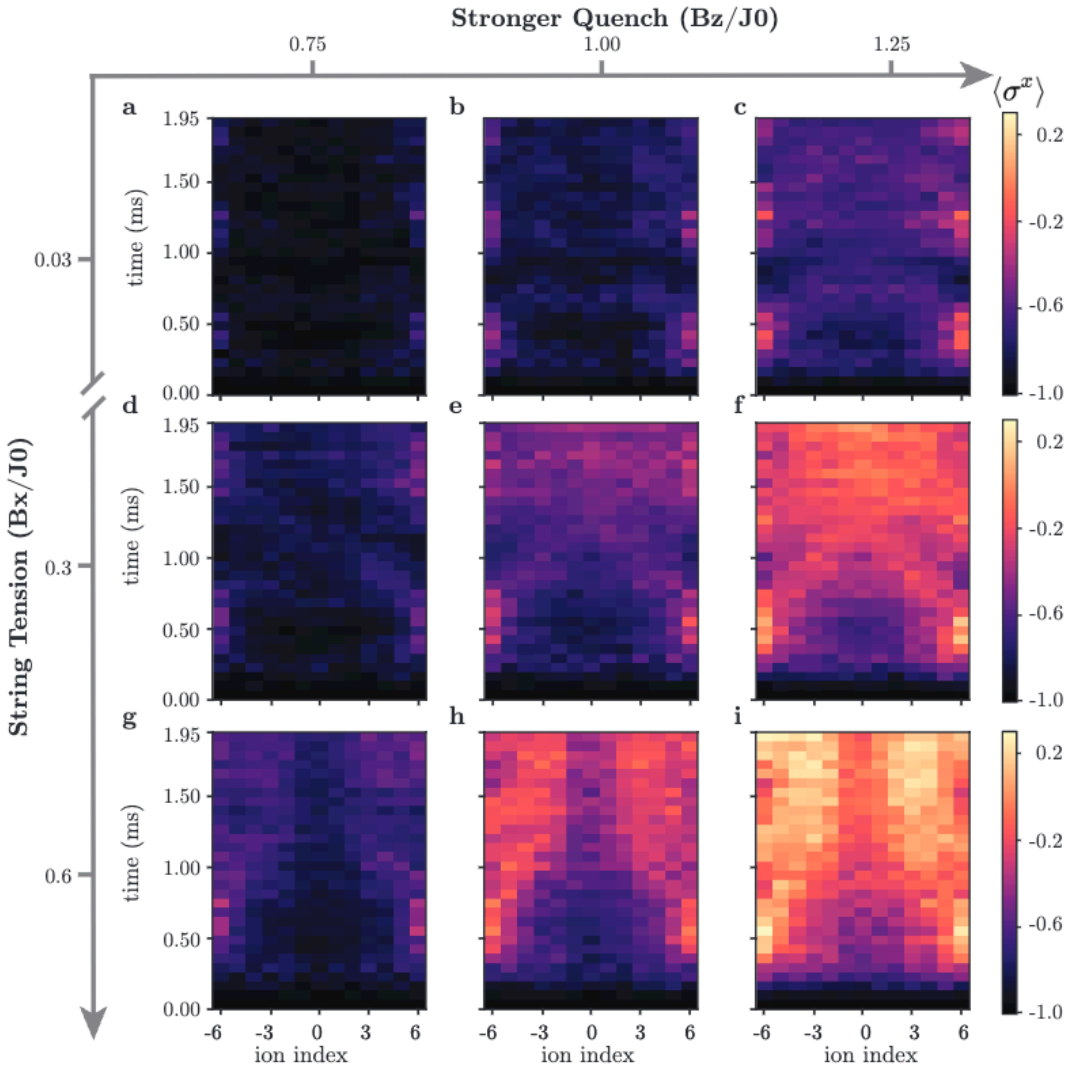


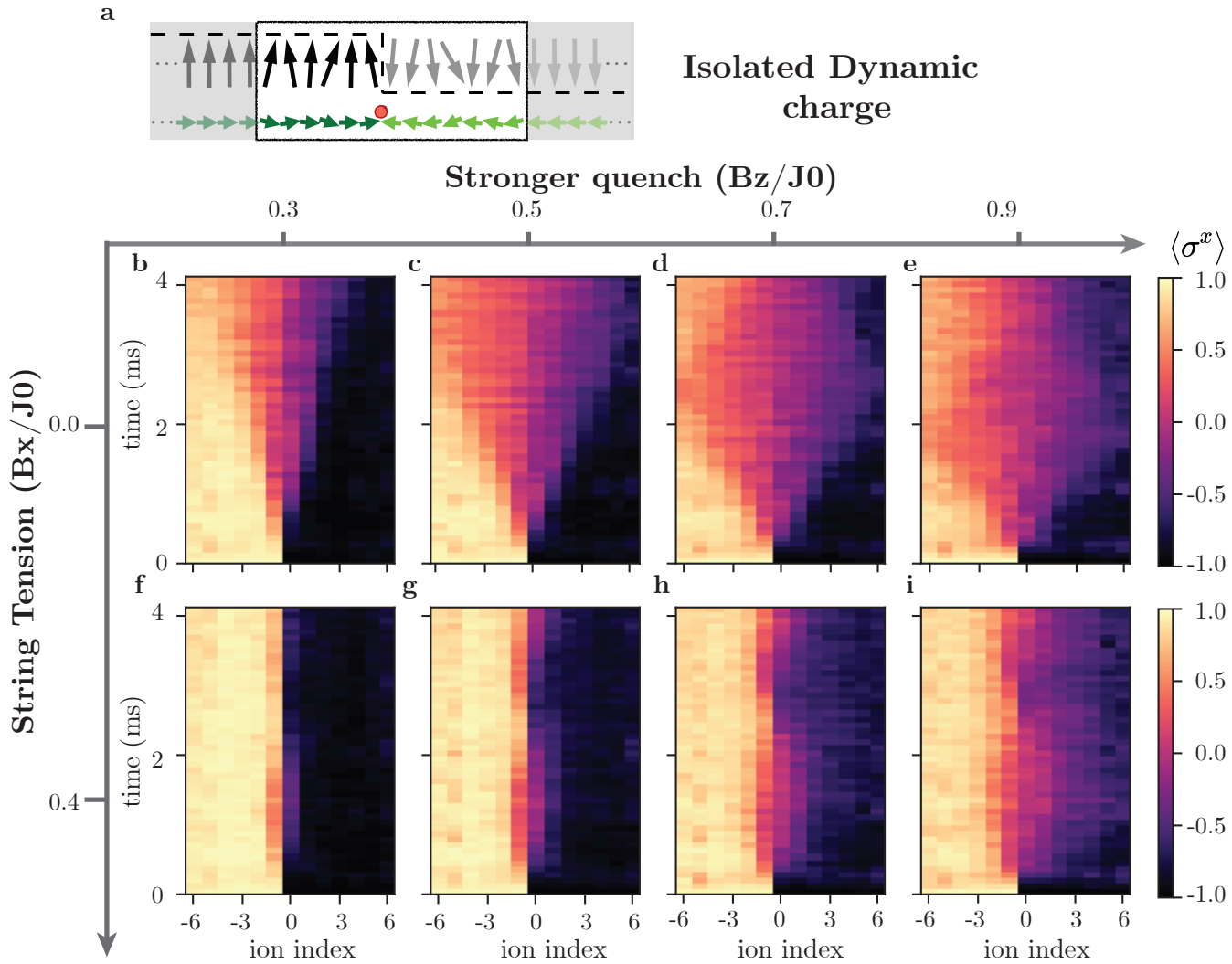


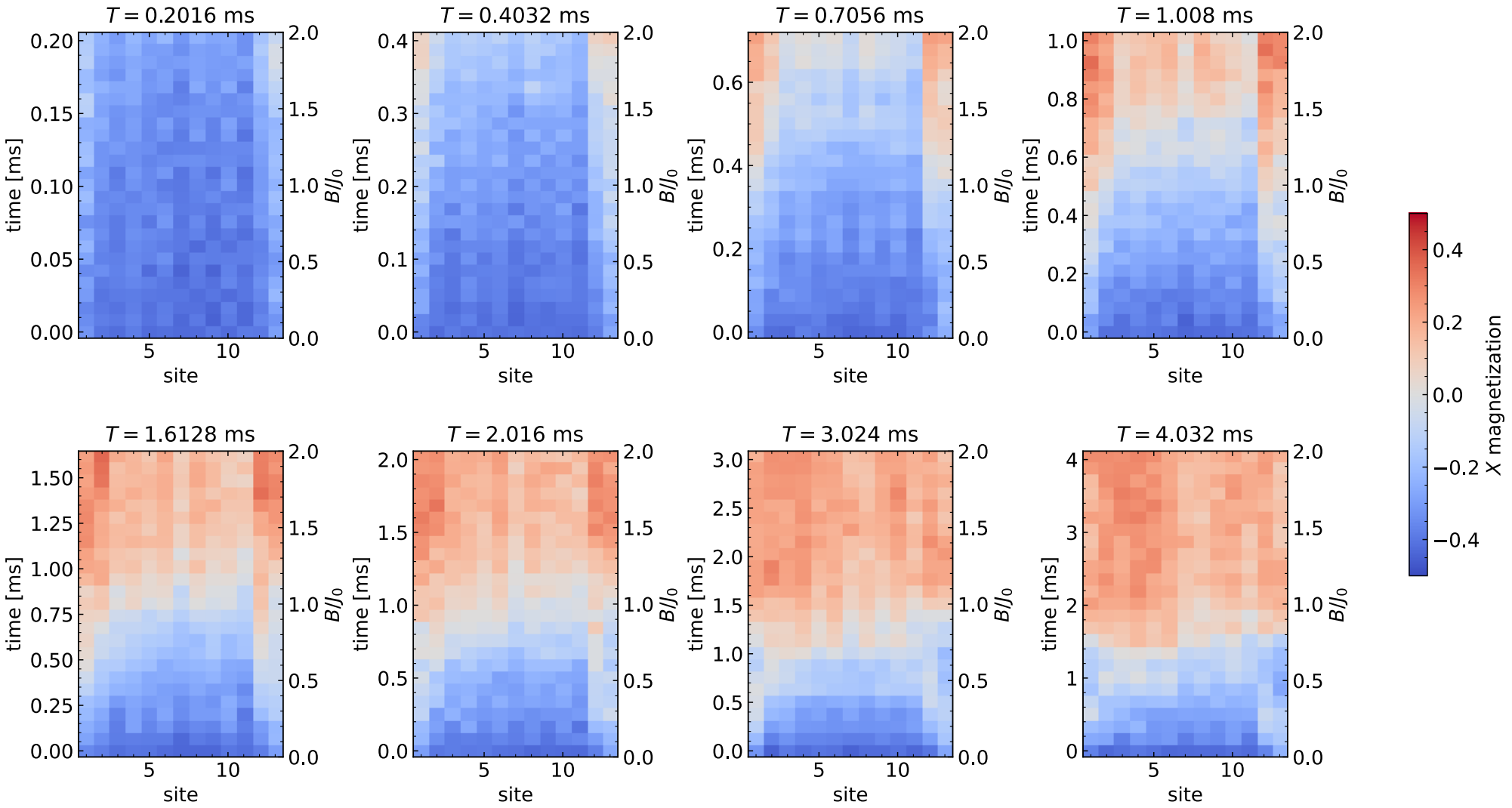


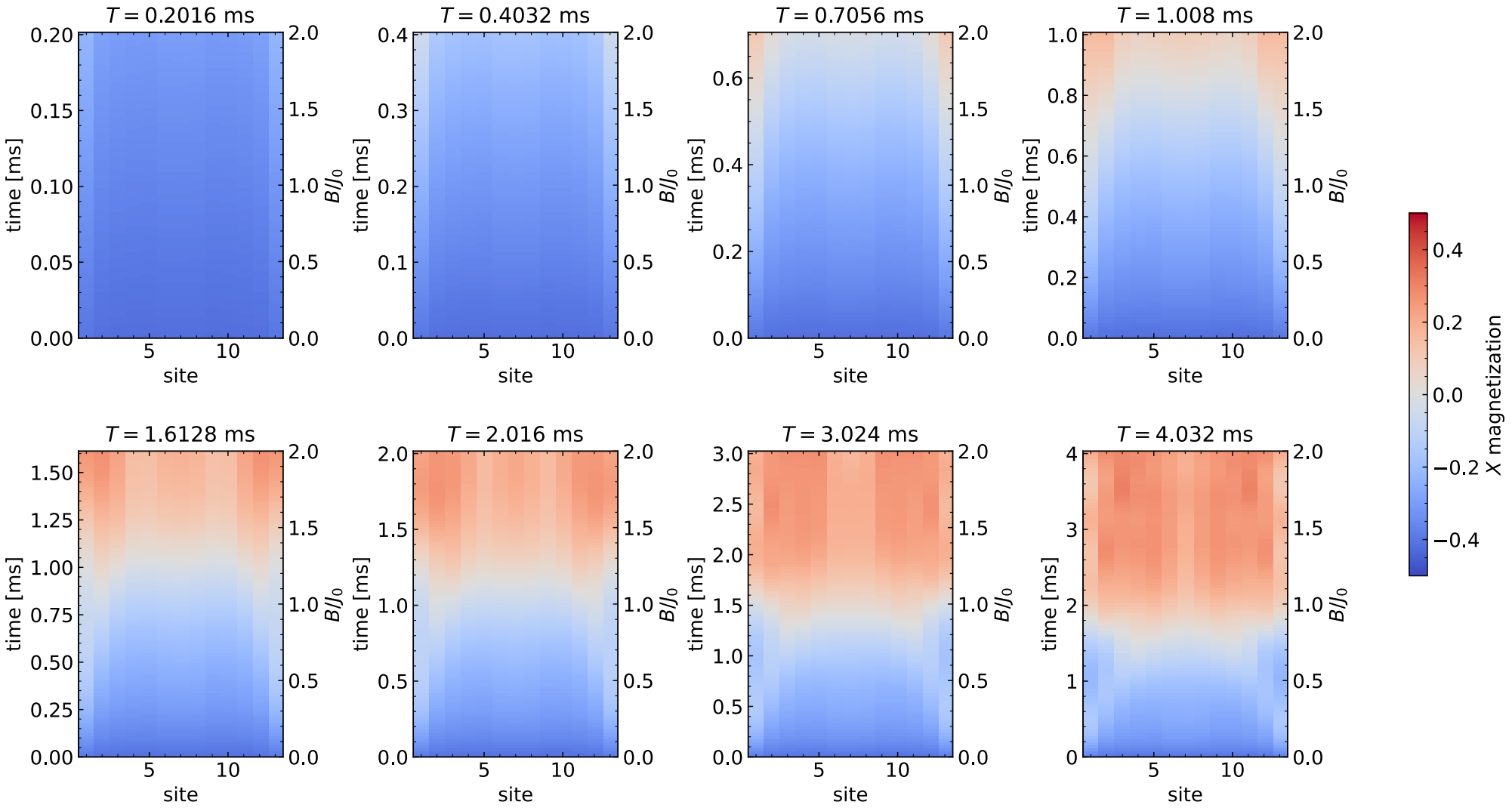

a
Dynamic Charge
b
Static Charge
c
d
time (ms)
1.95
1.50
1.00
0.50
0.00
-6
-3
0
3
6
ion index
$\langle \sigma^x \rangle$
1.0
0.5
0.0
-0.5
-1.0

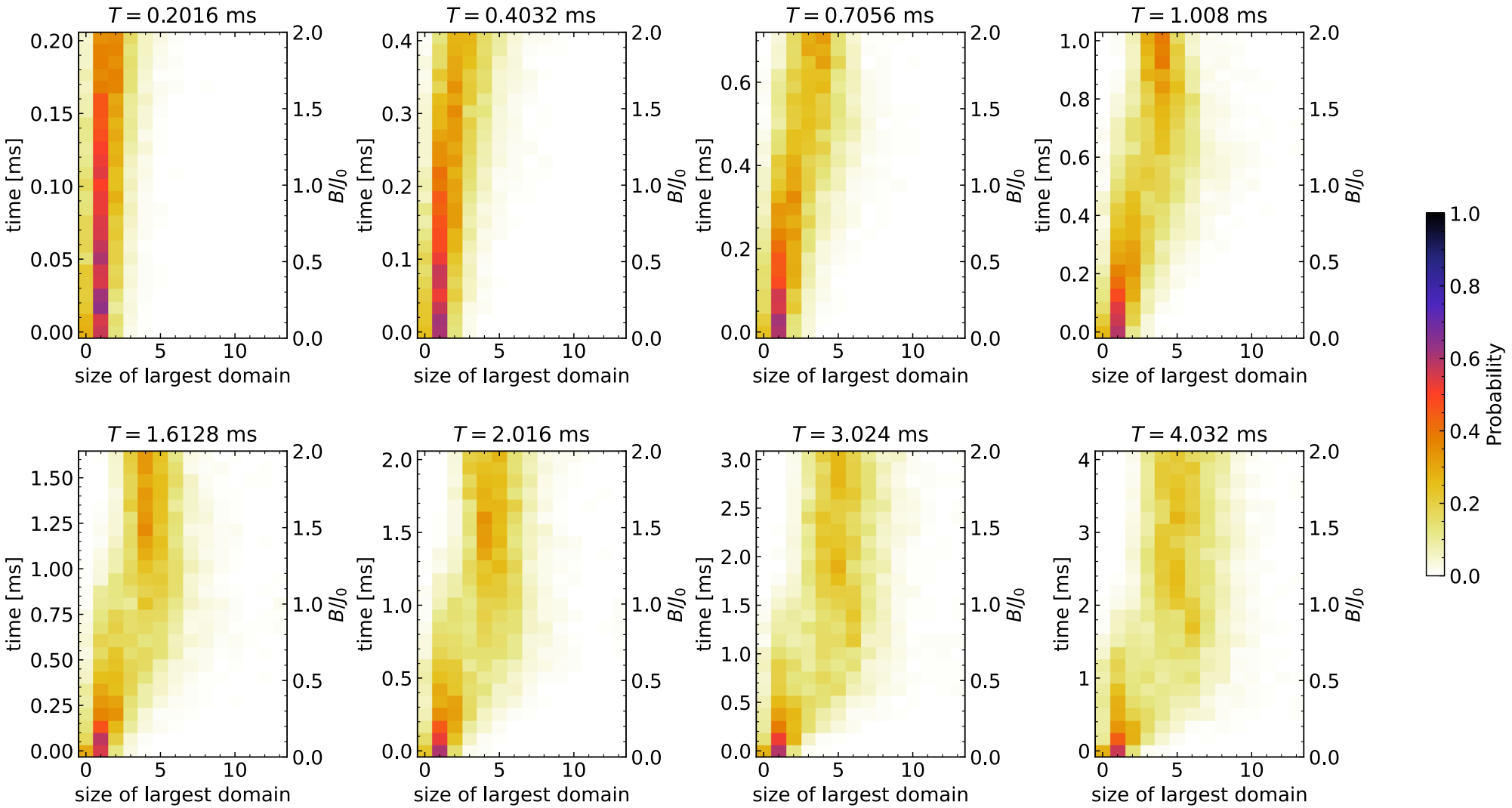
Quench

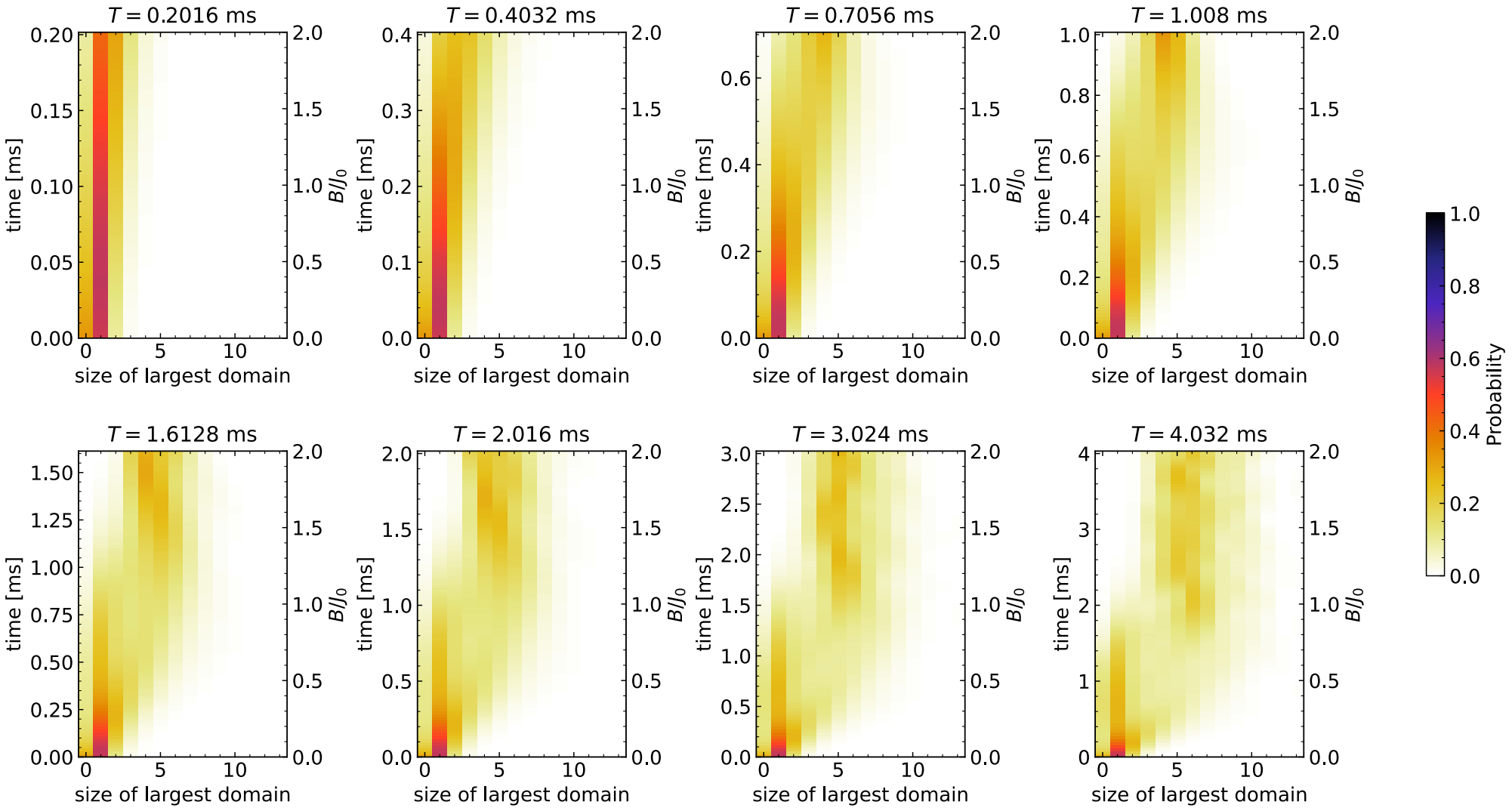

Stronger Quench (Bz/J0)
0.75
1.00
1.25
String Tension (Bx/J0)
0.03
0.3
0.6
a
b
c
d
e
f
g
h
i
time (ms)
1.95
1.50
1.00
0.50
0.00
ion index
-6
-3
0
3
6
$\langle \sigma^x \rangle$
0.2
-0.2
-0.6
-1.0

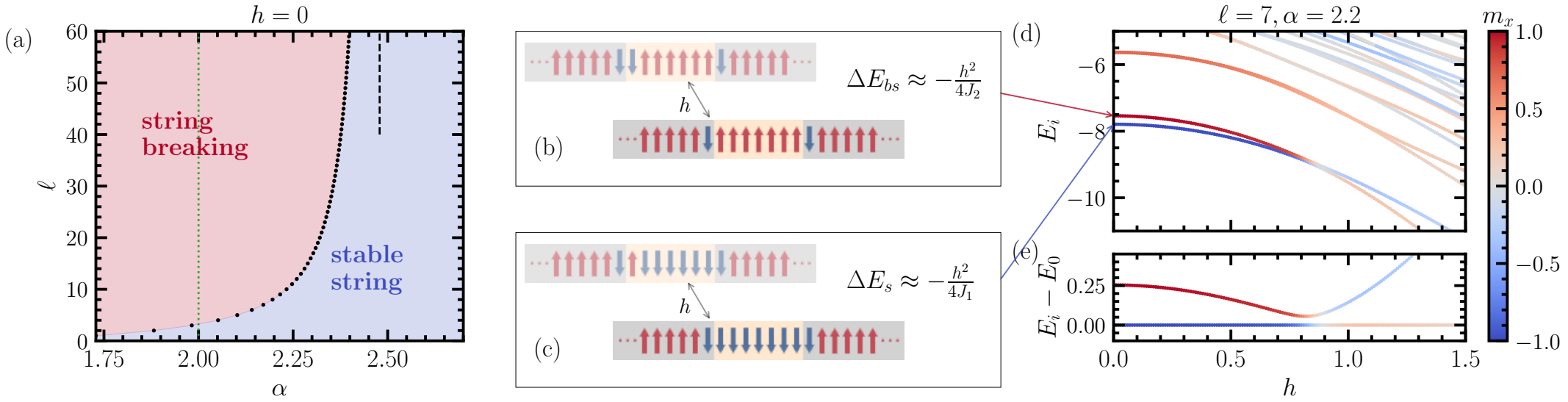

a
Isolated Dynamic charge
Stronger quench (Bz/J0)
0.3
0.5
0.7
0.9
String Tension (Bx/J0)
0.0
0.4
b
c
d
e
f
g
h
i
time (ms)
ion index
$\langle \sigma^x \rangle$
1.0
0.5
0.0
-0.5
-1.0

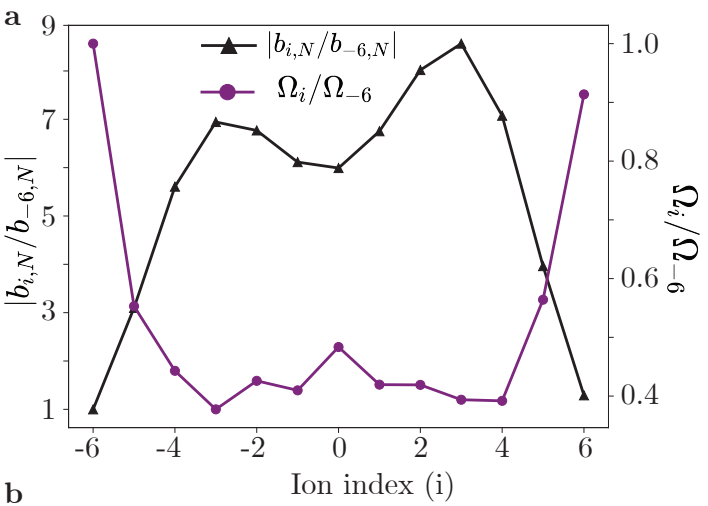

$T = 0.2016$ ms
$T = 0.4032$ ms
$T = 0.7056$ ms
$T = 1.008$ ms
$T = 1.6128$ ms
$T = 2.016$ ms
$T = 3.024$ ms
$T = 4.032$ ms
time [ms]
site
B/J_0
X magnetization


$T = 0.2016$ ms
$T = 0.4032$ ms
$T = 0.7056$ ms
$T = 1.008$ ms
$T = 1.6128$ ms
$T = 2.016$ ms
$T = 3.024$ ms
$T = 4.032$ ms
time [ms]
site
B/J_0
X magnetization

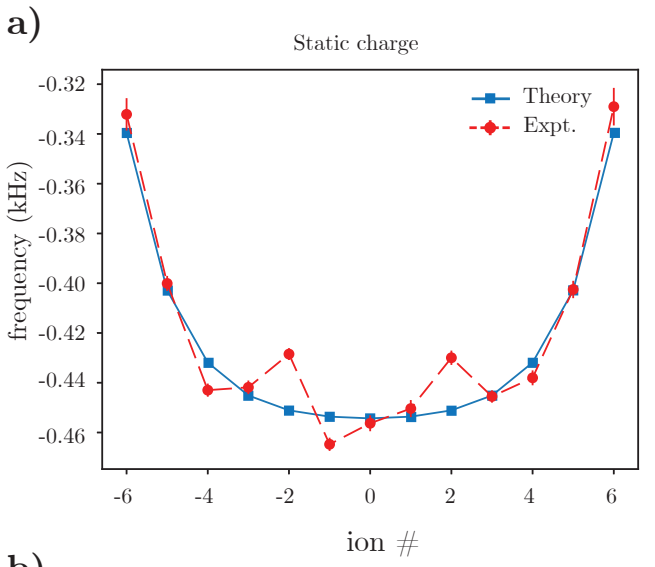

$T = 0.2016$ ms
$T = 0.4032$ ms
$T = 0.7056$ ms
$T = 1.008$ ms
$T = 1.6128$ ms
$T = 2.016$ ms
$T = 3.024$ ms
$T = 4.032$ ms
time [ms]
size of largest domain
B/J_0
Probability

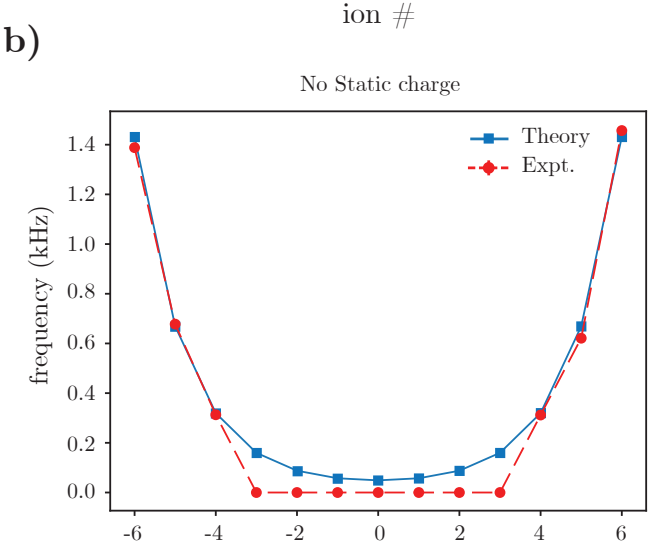

$T = 0.2016$ ms
$T = 0.4032$ ms
$T = 0.7056$ ms
$T = 1.008$ ms
$T = 1.6128$ ms
$T = 2.016$ ms
$T = 3.024$ ms
$T = 4.032$ ms
time [ms]
B/J_0
size of largest domain
Probability

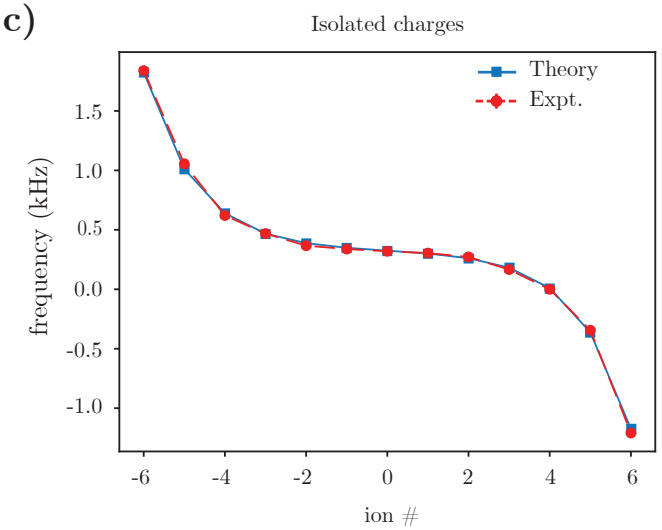

(a)
$h = 0$
string breaking
stable string
ℓ
α
(b)
$\Delta E_{bs} \approx -\frac{h^2}{4J_2}$
h
(c)
$\Delta E_s \approx -\frac{h^2}{4J_1}$
h
(d)
$\ell = 7, \alpha = 2.2$
E_i
(e)
$E_i - E_0$
h
m_x

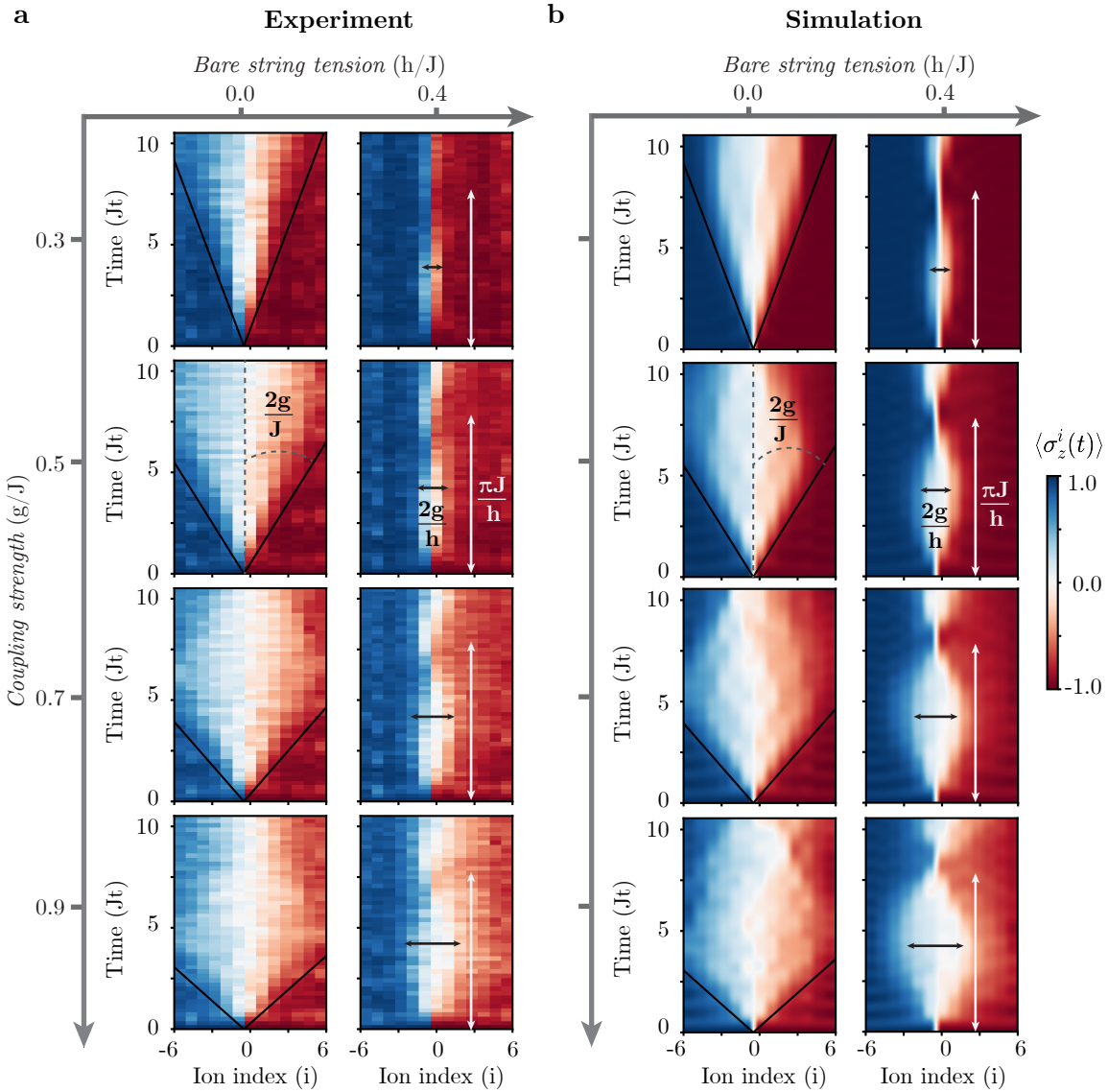


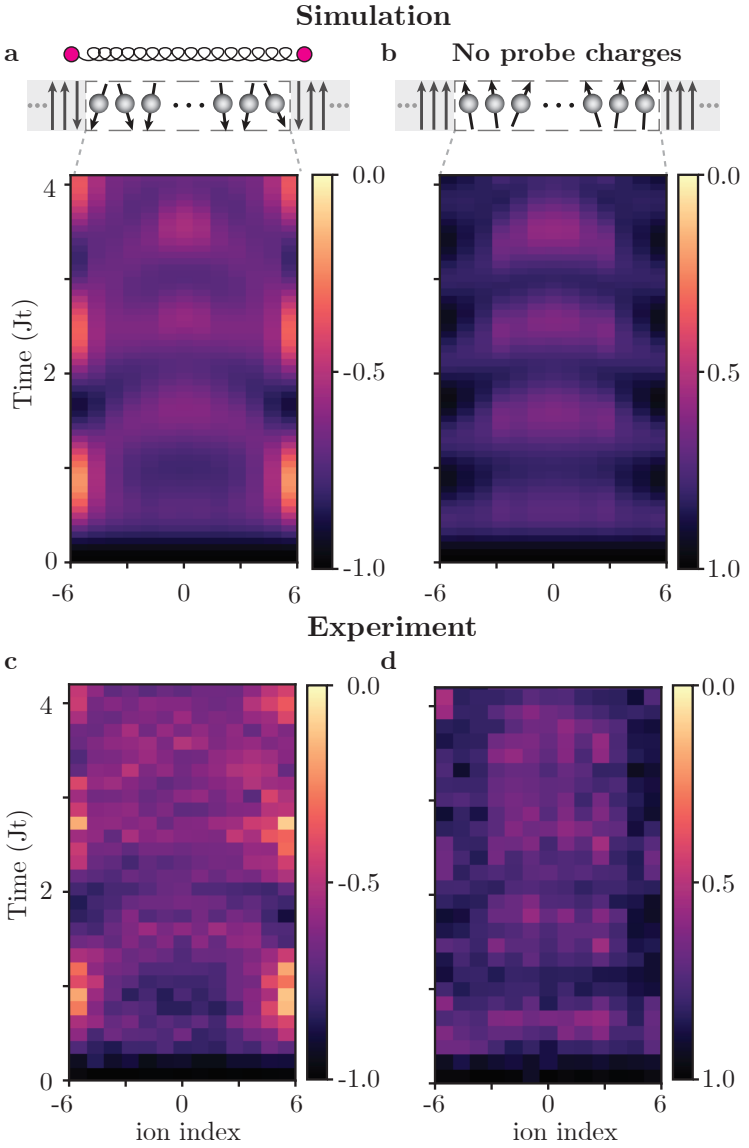
$$J_0 = 2\pi \times 0.68 \text{ kHz}$$

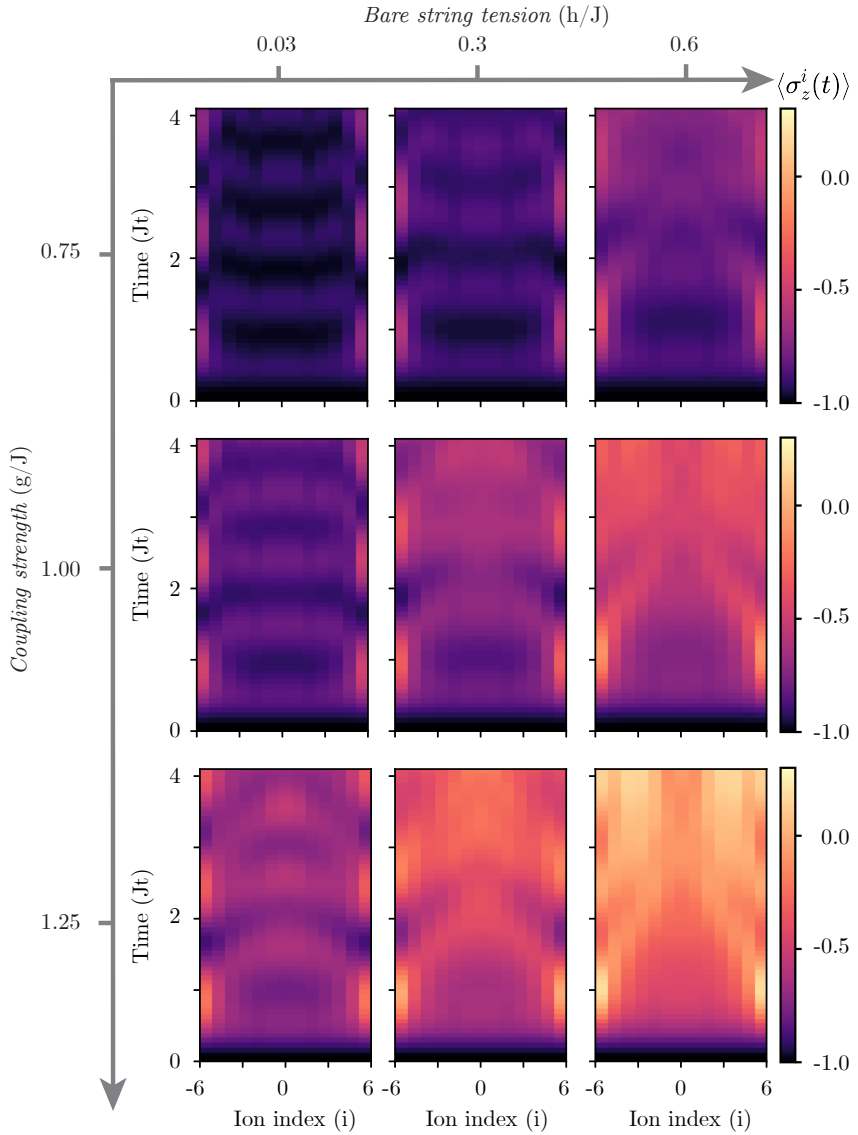


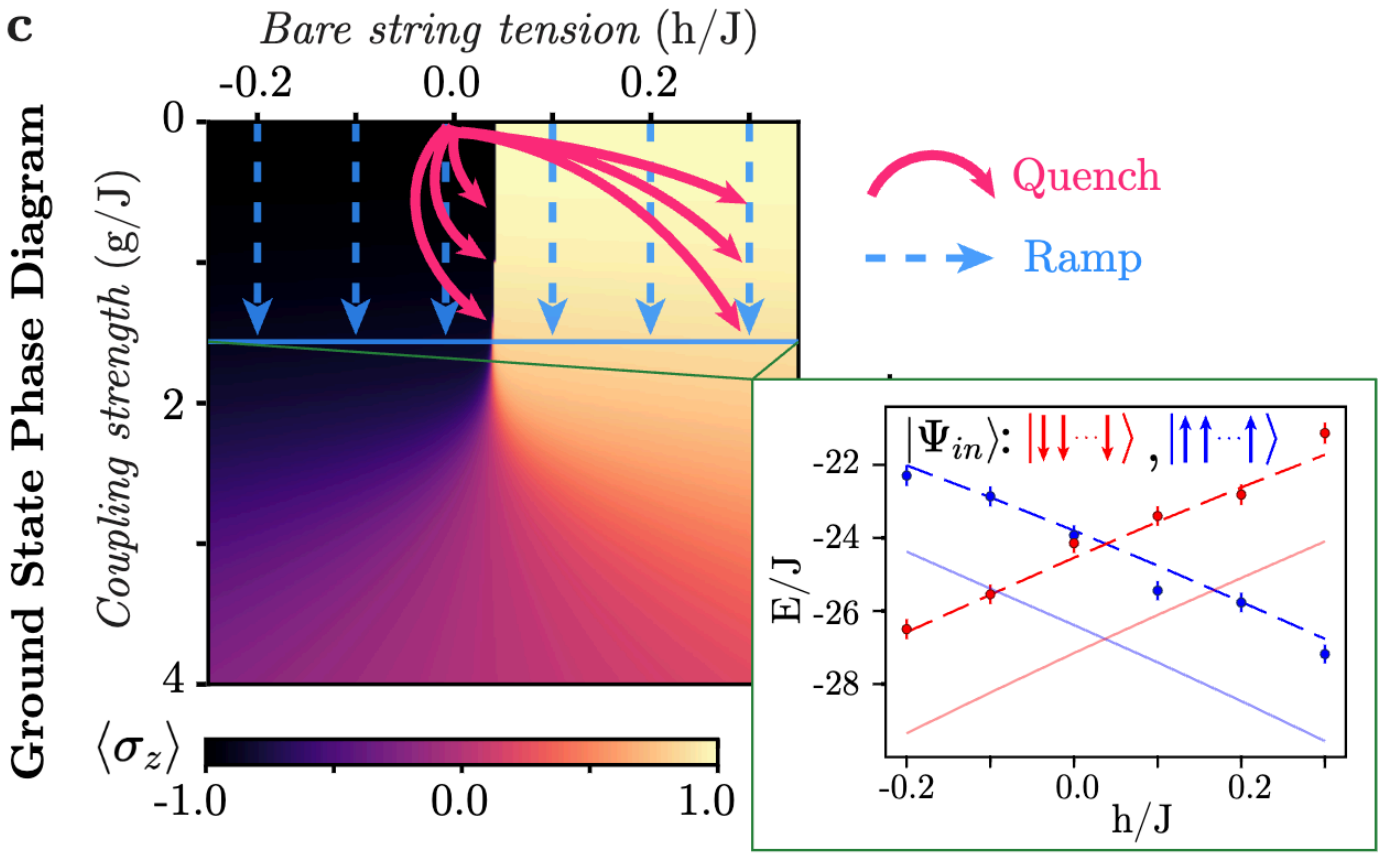





a
Experiment
b
Simulation
Bare string tension (h/J)
0.0
0.4
Coupling strength (g/J)
0.3
0.5
0.7
0.9
Time (Jt)
10
5
0
2g/J
2g/h
πJ/h
-6
0
6
Ion index (i)
⟨σ_z^i(t)⟩
1.0
0.0
-1.0


Simulation
a
b
No probe charges
Time (Jt)
0
2
4
-6
0
6
0.0
-0.5
-1.0
0.5
1.0
Experiment
c
d
ion index


Bare string tension (h/J)
0.03
0.3
0.6
$\langle \sigma_z^i(t) \rangle$
Coupling strength (g/J)
0.75
1.00
1.25
Time (Jt)
0
2
4
0.0
-0.5
-1.0
-6
0
6
Ion index (i)


c
Ground State Phase Diagram
Bare string tension (h/J)
-0.2
0.0
0.2
0
2
4
Coupling strength (g/J)
Quench
Ramp
⟨σz⟩
-1.0
0.0
1.0
|Ψin⟩: |↓↓···↓⟩ , |↑↑···↑⟩
-22
-24
-26
-28
E/J
-0.2
0.0
0.2
h/J