From high-energy physics to quantum simulation: Vacuum decay and meson collisions

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Alessio Lerose

UNIVERSITÉ DE GENÈVE

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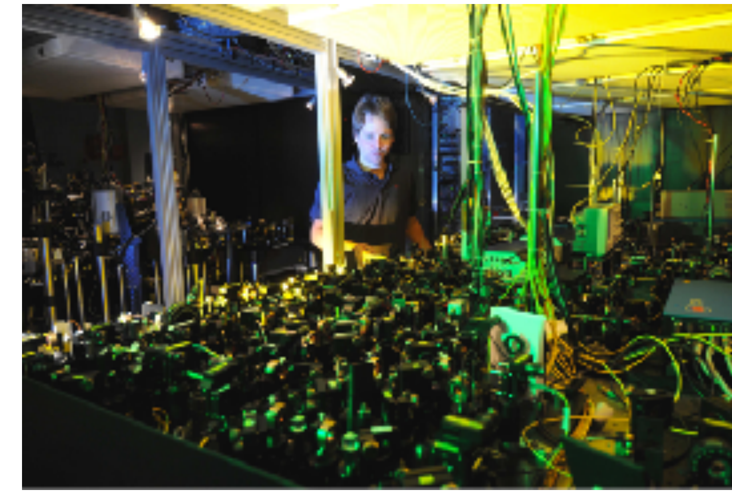
Beyond traditional quantum many-body physics

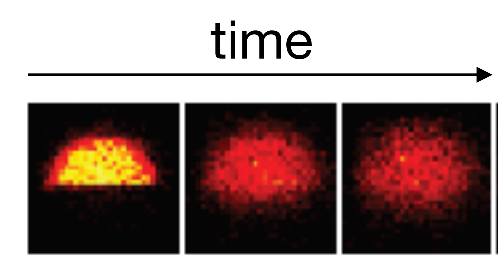
Atomic-Molecular-Optical toolbox → **“Synthetic matter”**

- Ultracold atoms
- Rydberg atom arrays
- Trapped ions
- Superconducting qubits
- …



$\neq$ “traditional” quantum many-body physics:

- Isolated (no phonon/heat bath) → **Coherent dynamics**



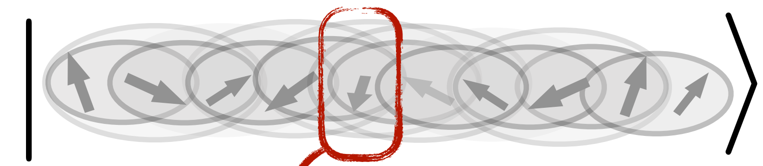
- Long time scales: $\sim 10^{-3}\,s$ vs $10^{-12}\,s$ → **Single-site, real-time resolution**

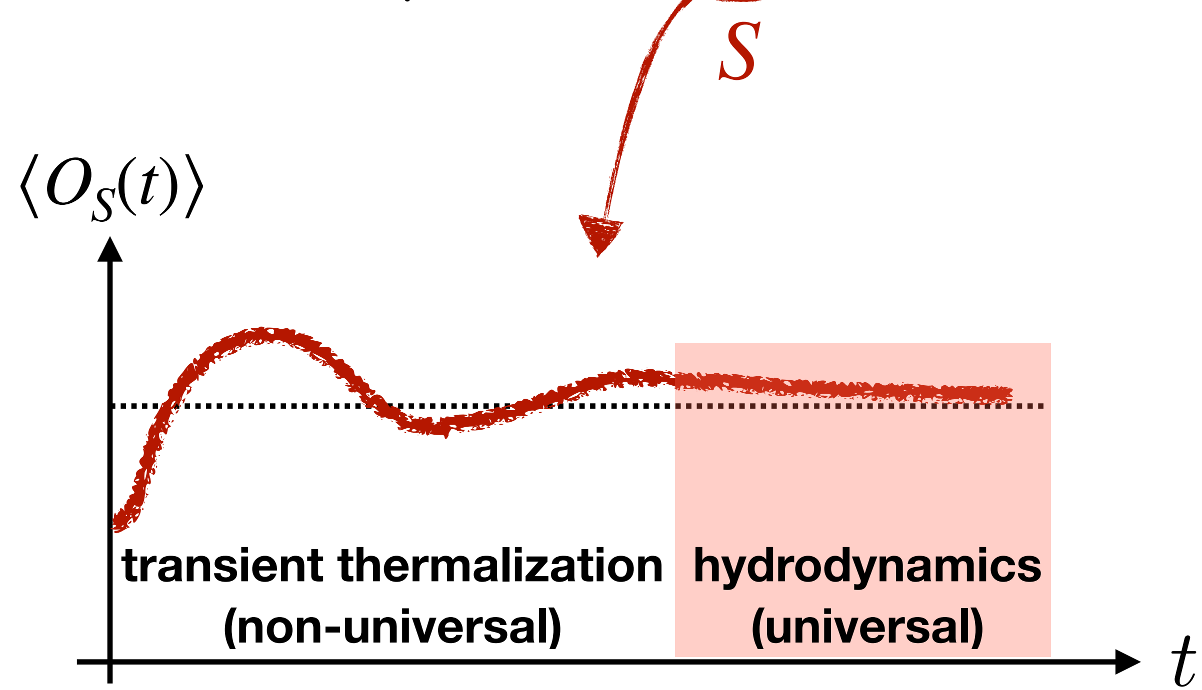
- Design dimensionality, lattice, interactions,… → **Tunability**

pictures: I. Bloch group @ Munich

Thermalization of isolated systems?

$$|\psi(t)\rangle = e^{-iHt}\,|\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\rangle \quad = $$





Thermalization of local observables?

$$\langle\psi(t)|O_S|\psi(t)\rangle \;\xrightarrow[t\to\infty]{?}\; \mathrm{Tr}\left(O_S\frac{e^{-\beta H}}{Z}\right)$$

Thermalizing systems

Effective thermal baths for subsystems

Emergent hydrodynamics

Ergodicity breaking systems $\longrightarrow$ **No (or slow) thermalization**

- Many-body localization
- Prethermalization
- Quantum many-body scars
- …

⇝ **Realize new (non-equilibrium) phases of matter**

review:
Polkovnikov et al., RMP (2011)

review:
Abanin et al., RMP (2020)

I
Non-equilibrium phases of synthetic matter inspired by familiar HEP phenomena

- P. P. Mazza, G. Perfetto, **A. Lerose**, M. Collura, A. Gambassi
  Suppression of transport in nondisordered quantum spin chains due to confined excitations
  Phys. Rev. B **99**, 180302(R) (2019)
- **A. Lerose**, F. M. Surace, P. P. Mazza, G. Perfetto, M. Collura, A. Gambassi
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  Phys. Rev. Lett. **129** (12), 120601 (2022)
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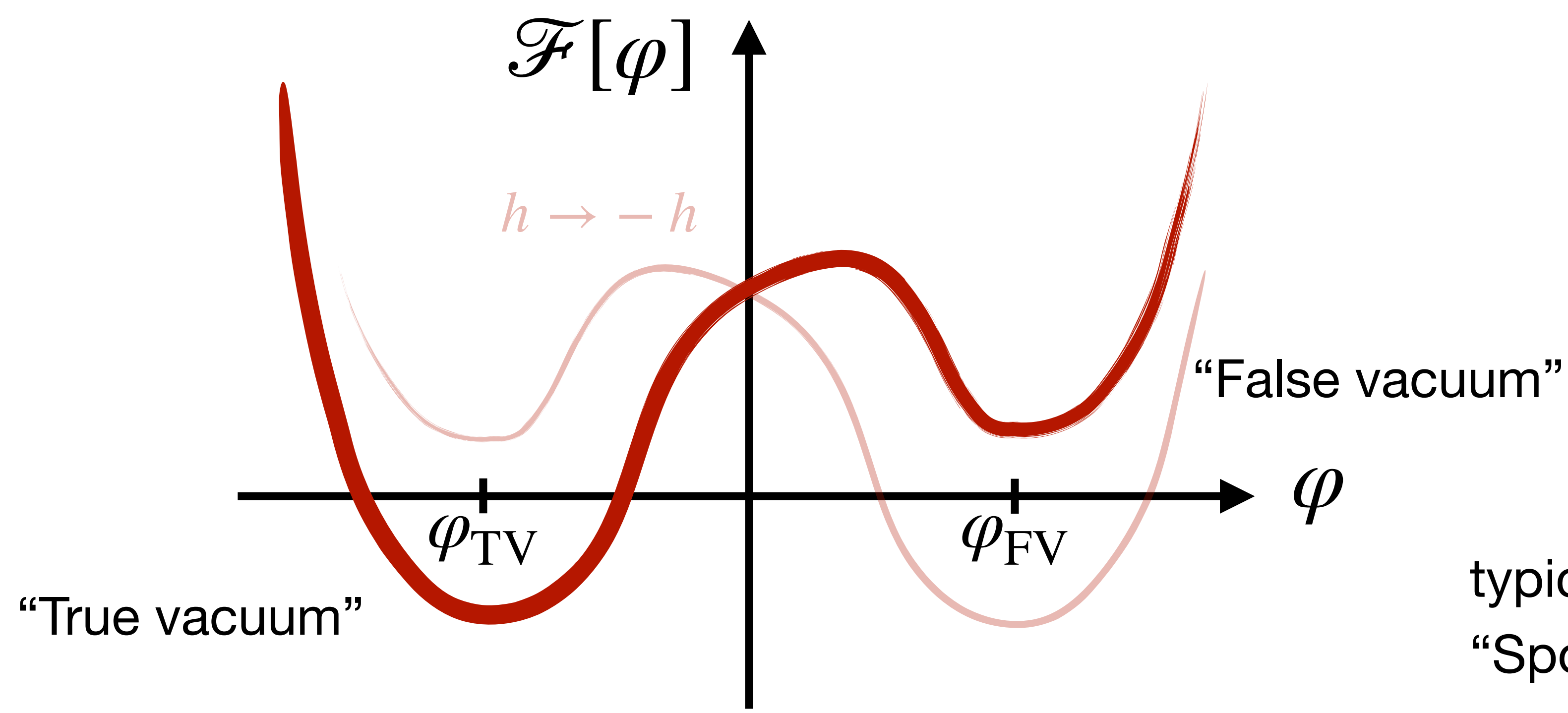
  Discrete time-crystalline response stabilized by domain-wall confinement
  Phys. Rev. X **12** (3), 031037 (2022)

II
Towards quantum simulation of real-time HEP dynamics

- F. M. Surace, P. P. Mazza, G. Giudici, **A. Lerose**, A. Gambassi, M. Dalmonte
  Lattice gauge theories and string dynamics in Rydberg-atom quantum simulators
  Phys. Rev. X **10**, 021041 (2020)
- F. M. Surace, **A. Lerose**
  Scattering of mesons in quantum simulators
  New Journal of Physics **23** (2021)
- Ongoing work with E. Bennewitz, B. Ware, A. Schuckert, F. M. Surace, A. Gorshkov, Z. Davoudi (theory) & C. Monroe group (experiment)
  Observation of string breaking & meson scattering dynamics with trapped ions

Multiple competing equilibria

First-order phase transition



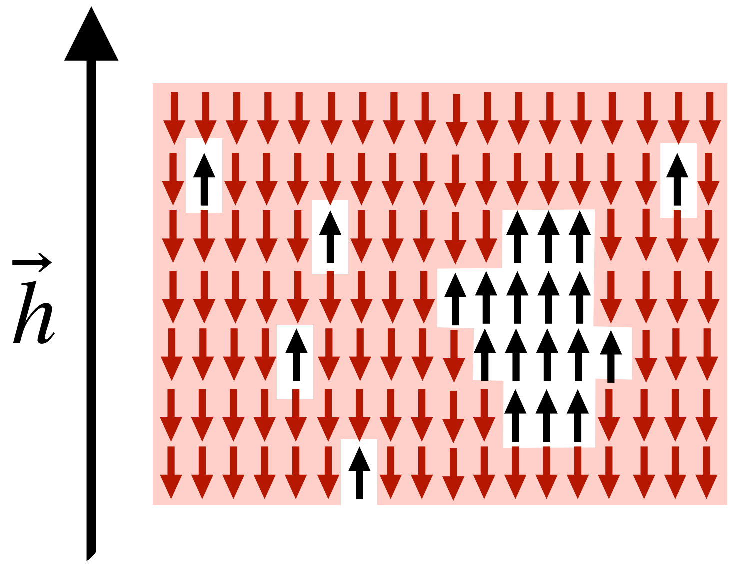
typically:
"Spontaneous + Explicit" symmetry breaking

$$H[\varphi] = \int dx \Big(|\nabla \varphi|^2 + m\varphi^2 + \lambda\varphi^4 + h\varphi \Big)$$

Dynamics from metastable equilibrium state? $\langle \varphi(x,0) \rangle = \varphi_{\rm FV} \longrightarrow \langle \varphi(x,t) \rangle = ?$

Stat-phys: Thermally activated nucleation

Magnetic nucleation in permanent magnets



Ice nucleation in supercooled water

Stochastic dynamics of a spin lattice or classical gas

Classical Nucleation Theory: (~ Transition State Theory in chemistry)

$$P_{\mathrm{FV}}(t) \sim \exp(-\Gamma V t)$$

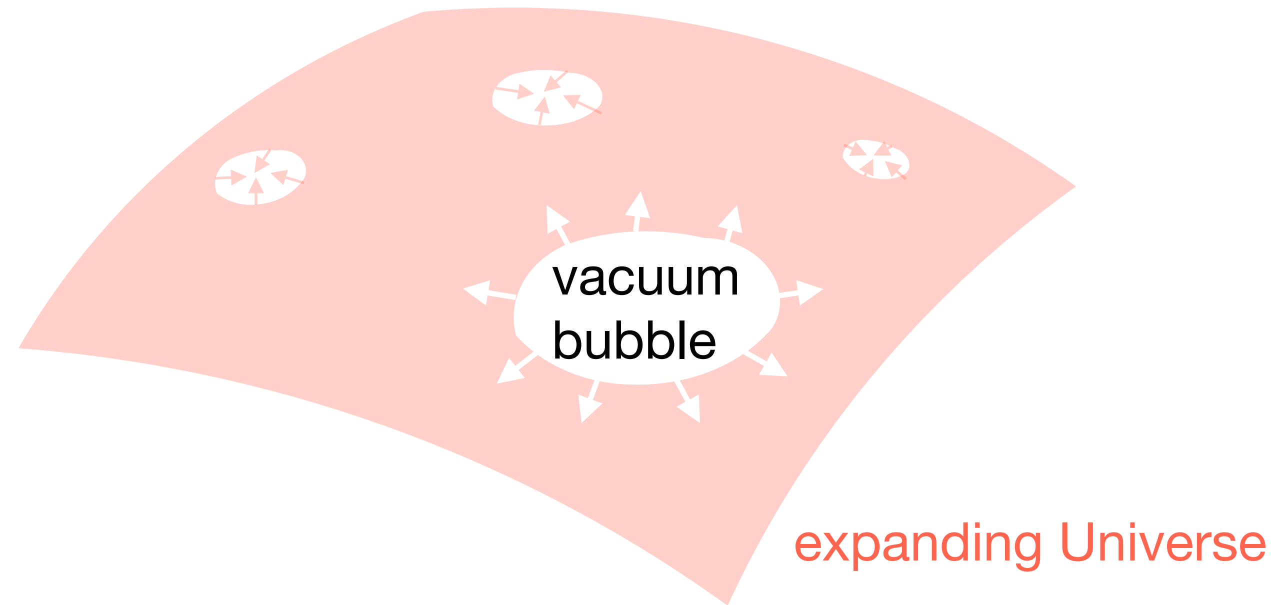
$$\langle \varphi(x,t) \rangle \sim \varphi_{\mathrm{FV}} \exp(-\Gamma V_{\mathrm{b}} t)$$

$$\Gamma \sim A \exp\left(-\frac{B}{k_B T}\right)$$ → non-perturbative origin in T

decay driven by rare thermal fluctuation

Cosmology: False-vacuum decay scenario

Decay of “supercooled” early Universe



Unitary dynamics of relativistic quantum fields

Instanton theory of tunneling decay: *Coleman, PRD (1977)*

$$P_{\mathrm{FV}}(t) \sim \exp(-\Gamma V t)$$

$$\langle \varphi(x,t) \rangle \sim \varphi_{\mathrm{FV}} \exp(-\Gamma V_{\mathrm{b}} t)$$

$$\Gamma \sim A \exp\left(-\frac{B}{\hbar} \right)$$ → non-perturbative origin in $\hbar$

decay driven by “atypical” quantum fluctuation

Synthetic matter: Coherence and Lattice

Both in stat-phys and cosmology context:

✳ Non-perturbative activation law by "extremum event"

✳ Genuine many-body fluctuation phenomenon, locality of interactions crucial *(no mean-field theory!)*

✳ True-vacuum critical bubble expands indefinitely

Synthetic matter?

✳ No thermostat (i.e. no bath)

✳ Optical lattice / tweezers

incoherent noisy dynamics	**coherent dynamics**	coherent dynamics
lattice	**lattice**	continuum spacetime

?

Suprisingly, new phenomena!

Case study: Quantum Ising model

Prototypical model of synthetic matter:

$$H = -J \sum_{\langle \mathbf{r},\mathbf{r}' \rangle} \sigma^z_{\mathbf{r}} \sigma^z_{\mathbf{r}'} - g \sum_{\mathbf{r}} \sigma^x_{\mathbf{r}} - h \sum_{\mathbf{r}} \sigma^z_{\mathbf{r}}$$

- Rydberg atom arrays
- Trapped ions
- Superconducting qubits
- ...

False vacuum decay rate bounded via Rigorous prethermalization theory

Large $J \gg h, g$:

cf. Abanin, De Roeck, Ho, Huveneers, CMP (2017)

Quasilocal unitary transformation $U = \exp\Big(\mathcal{O}(1/J)\Big)$

$$\left|\left|\left| \left[U\Big(\sum_{\langle \mathbf{r},\mathbf{r}' \rangle} \sigma^z_{\mathbf{r}} \sigma^z_{\mathbf{r}'} \Big) U^\dagger, H \right] \right|\right|\right| \leq \Gamma \equiv A \exp(-BJ)$$

More general regimes:

$J, h \gg g$ — *cf. De Roeck, Verreet, arxiv (2019)*

$J \gtrsim g \gg h$ — *cf. Yin, Lucas, arxiv (2022), Rutkevich, PRB (1999)*

Clear origin of non-perturbative activation law

False-vacuum dynamics in Quantum Ising chain

Rutkevich, PRB (1999)
AL et al., PRB (2020)
Verdel et al., PRB (2020)
Lagnese et al., PRB (2021)

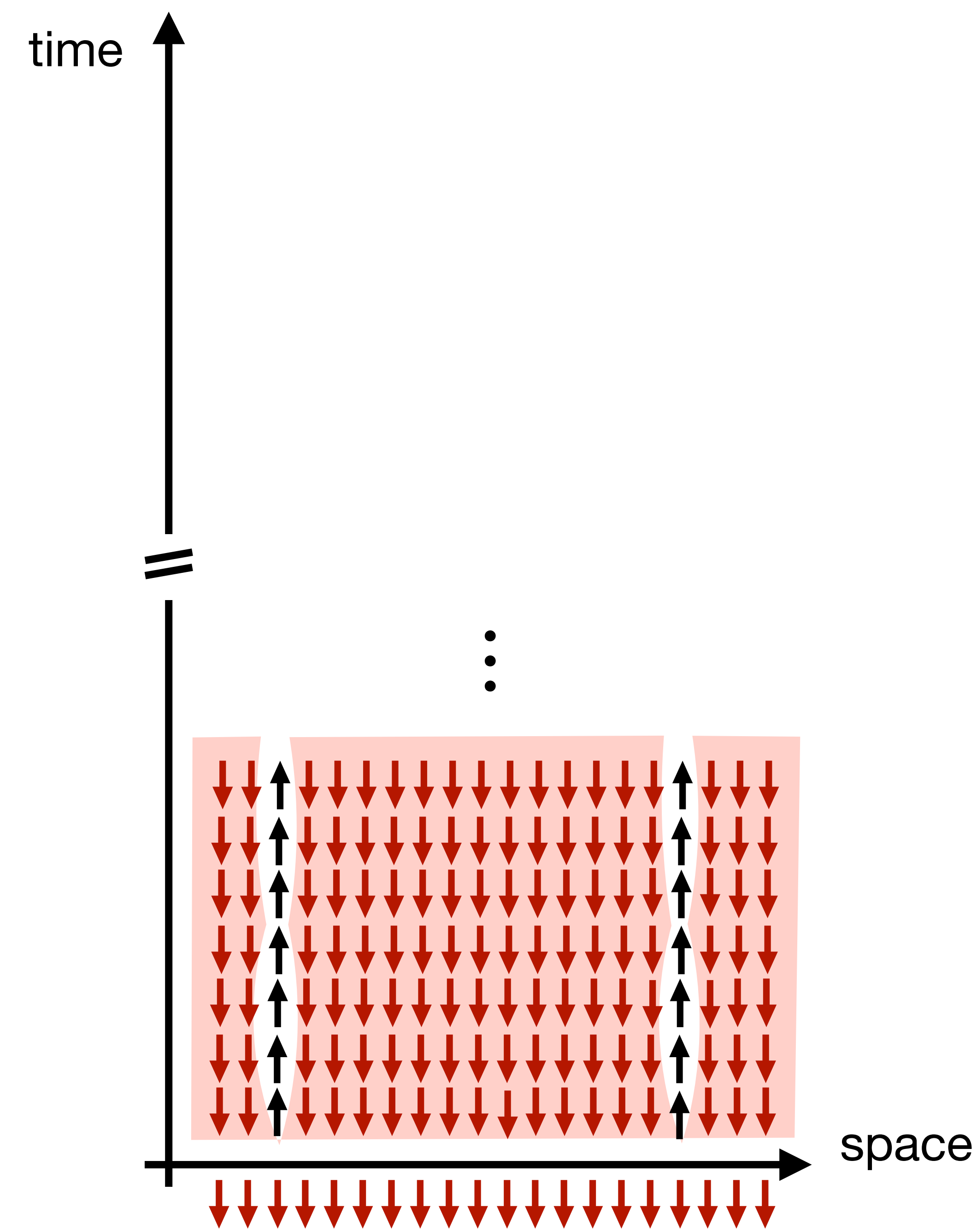
$$H = -J\sum_j \sigma_j^z \sigma_{j+1}^z - g\sum_j \sigma_j^x - h\sum_j \sigma_j^z$$

Degenerate vacua for $h = 0$: $\quad |\uparrow\rangle \qquad |\downarrow\rangle$

Exponentially slow materialization of true-vacuum bubbles!

(slow violation of prethermal conservation law)

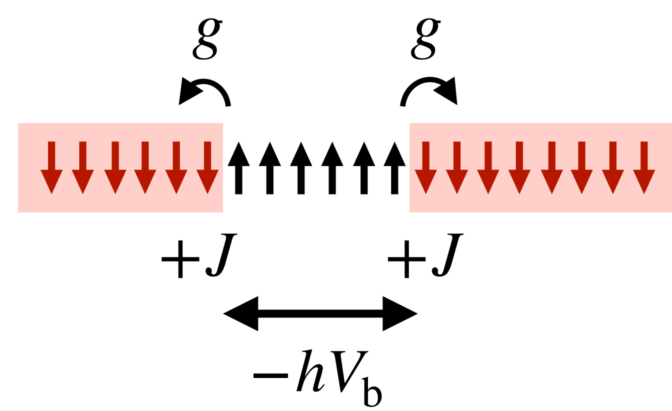
Quench dynamics $\quad g_i \to g_f\,, \quad h \neq 0$



Resonant bubbles

AL et al., PRB (2020)

Bubble is **resonant**:
domain walls cost ~ domain area gain



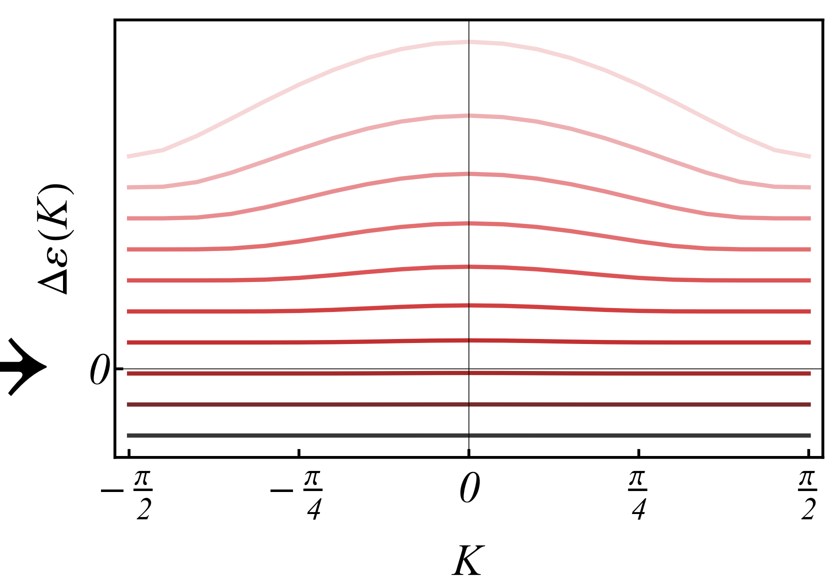
many spin flips involved
→ non-perturbative process

Effective two-domain-wall problem: **"Anti-Meson" spectrum**

(computed analytically for large J)

Wannier-Stark localization of domain walls in confining potential
(→ lattice effect!)

Resonant "anti-meson" (or "vacuum bubble") →



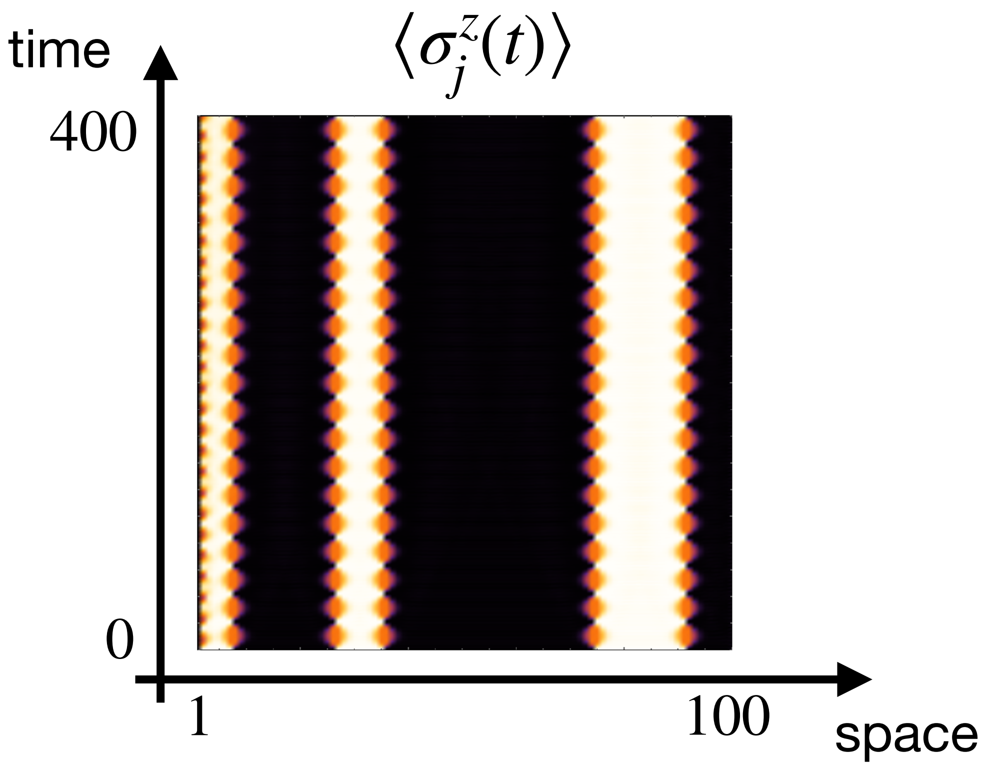
Dynamics of vacuum bubbles

AL et al., PRB (2020)

So far $\sim$ Coleman. Post-decay scenario?

Numerical experiment: Dynamics of isolated bubbles

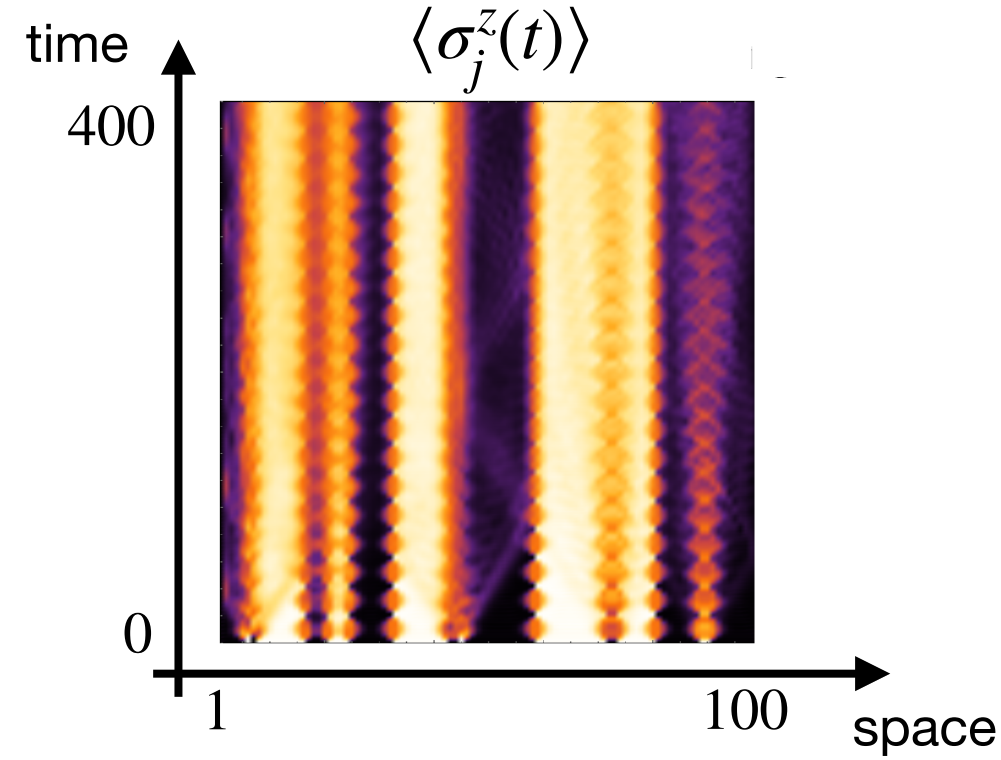
Matrix-Product State simulations of dynamics (TEBD, $\chi = 256$)
(here $J = 5$, $g = 1$, $h = 0.75$)



False-vacuum decay scenario in 1d synthetic matter

AL et al., PRB (2020)

Many-body dynamics?
Residual interaction effects?

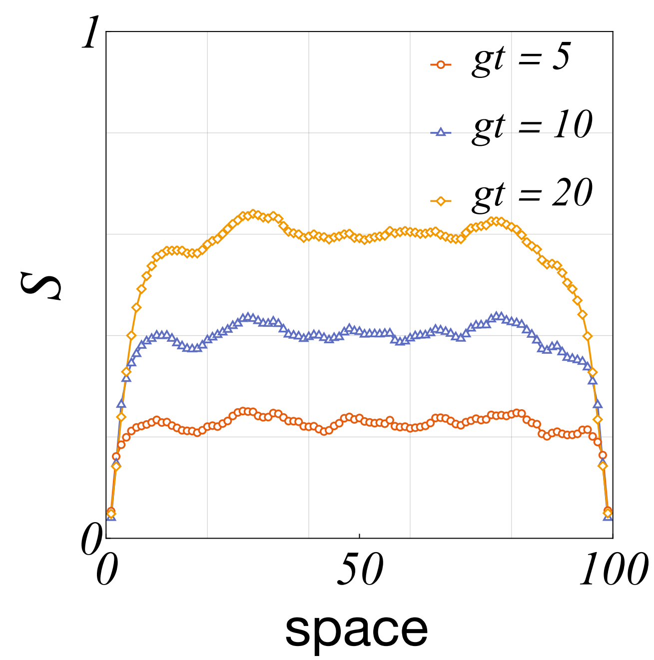


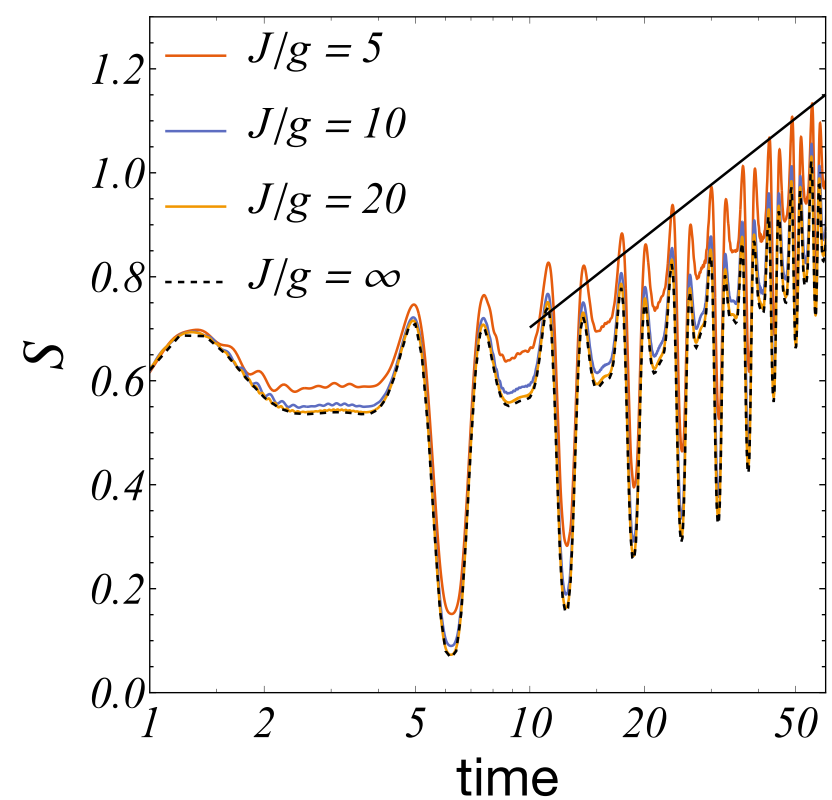
Numerical experiment: Dynamics of dilute domain-walls

Broad non-ergodic regime, no local relaxation

Slow unbounded entanglement growth $\sim$ MBL dynamics!

- Averaging over random initial state
- Regular array of domain walls
- Finite vs infinite J
- …





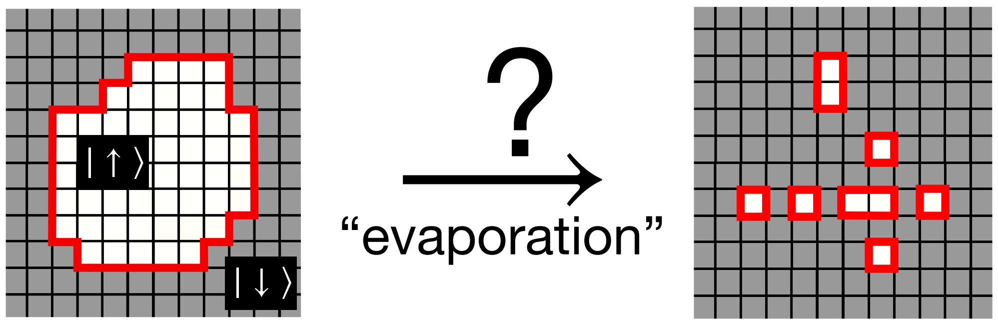
No theory for $S(t)$ yet…

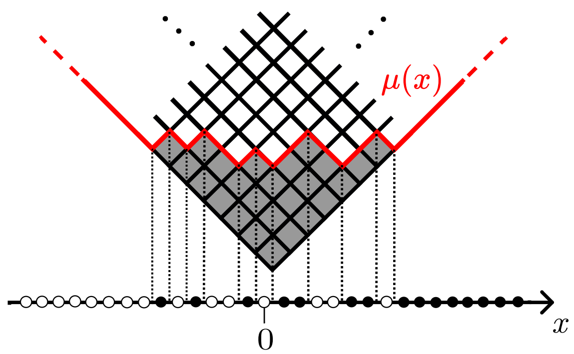
False-vacuum decay scenario in 2d synthetic matter

Balducci, AL et al., PRL (2022)

2d quantum Ising model $H = -J\sum_{\langle \mathbf{r},\mathbf{r}'\rangle} \sigma^z_{\mathbf{r}}\sigma^z_{\mathbf{r}'} - g\sum_{\mathbf{r}} \sigma^x_{\mathbf{r}} - h\sum_{\mathbf{r}} \sigma^z_{\mathbf{r}}$

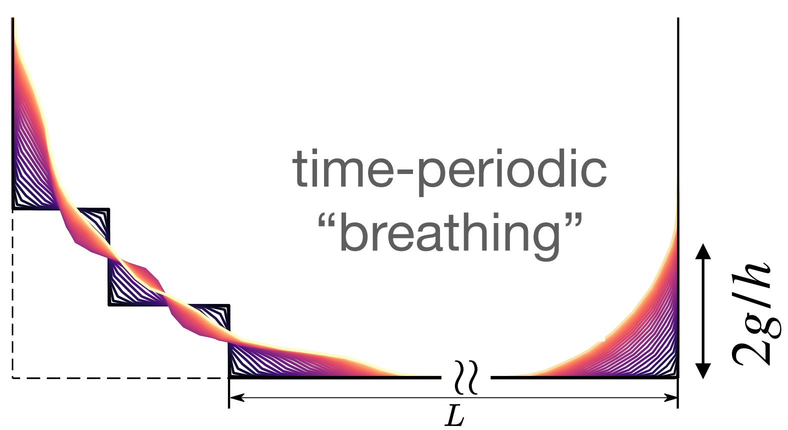
Unitary evolution of a large true-vacuum bubble?





“Holographic” mapping to 1d fermions:

$$H_{\mathrm{F}} = -g\sum_{x\in\mathbb{Z}}\left(\psi^\dagger_x\psi_{x+1} + \mathrm{h.c.}\right) + 2h\sum_{x\in\mathbb{Z}} x\,\psi^\dagger_x\psi_x \qquad (J=\infty)$$



Exact interface dynamics:

$$\langle \mu(x,t)\rangle = \frac{2g\,|\sin(ht)|}{|h|}\,\Omega\left(\frac{hx}{2g\sin(ht)}\right)$$

Okunkov function
(~ Plancherel measure on large Young diagrams)

Persistent oscillations, memory of initial shape $T \sim e^{cL\log L}$

Finite-J corrections break integrability

$$V_{\mathrm{F}} = -\frac{g^2}{4J}\sum_x\left(\psi^\dagger_x\psi_{x+2} + \mathrm{h.c.}\right) + \frac{g^2}{4J}\sum_x\left(2\psi^\dagger_x\psi^\dagger_{x+1}\psi_{x+1}\psi_{x+2} + \mathrm{h.c.} - 3\psi^\dagger_x\psi_x\psi^\dagger_{x+1}\psi_{x+1}\right) \longrightarrow$$

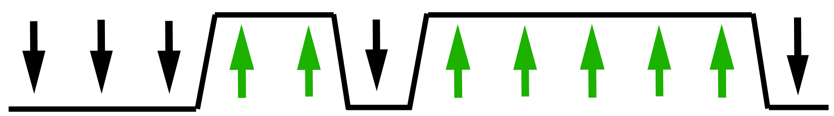
Stark MBL
(very slow subdiffusion)

Schulz et al., PRL (2019), van Nieuwenburg et al., PNAS (2019)

Connection with Lattice Gauge Theory

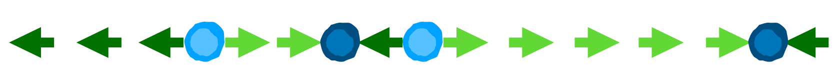
Exact mapping between (1+1)-d LGTs and quantum spin chains with **local** interactions:

AL et al., PRB (2020)
cf. Zohar, Cirac (2019-…)
Borla et al., SP (2021)



Quantum Ising chain

$$H = \sum_i -J\sigma_i^z\sigma_{i+1}^z - g\sigma_i^x - h\sigma_i^z$$



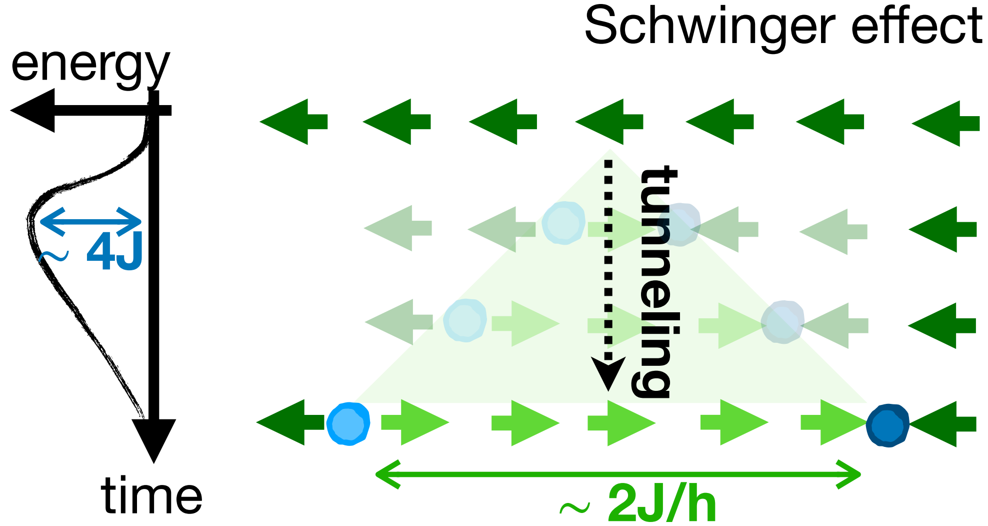
$\mathbb{Z}_2$ LGT (or $U(1)$ QLM)

$$H = \sum_i m c_i^\dagger c_i - w[(c_i - c_i^\dagger)\,\sigma_{i,i+1}^x\,(c_{i+1} + c_{i+1}^\dagger)] + \tau\sigma_{i,i+1}^z$$

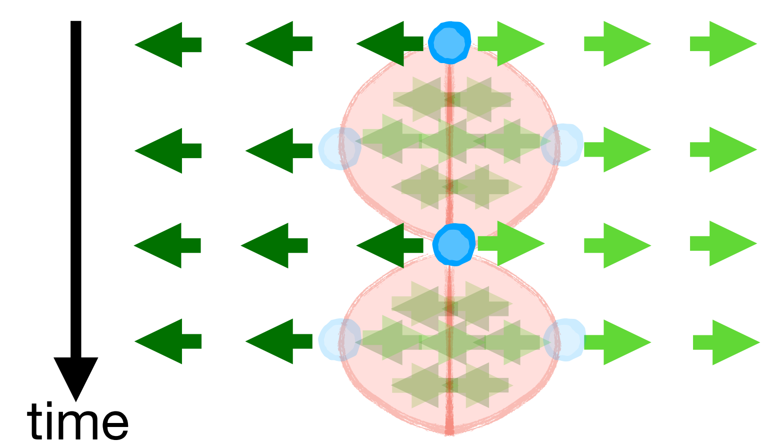
LGT interpretation of slow thermalization:

AL et al., PRB (2020)

Schwinger effect



Bloch oscillations

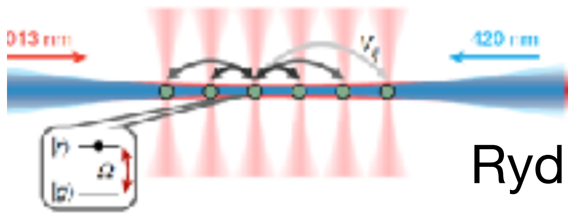


NB Closely connected with fracton dynamics, Stark MBL

Quantum simulation

Exact mapping → **Simulate real-time LGT dynamics with state-of-the-art quantum simulators**

Surace, AL et al., PRX (2020)
Surace, AL, NJP (2021)
work in progress

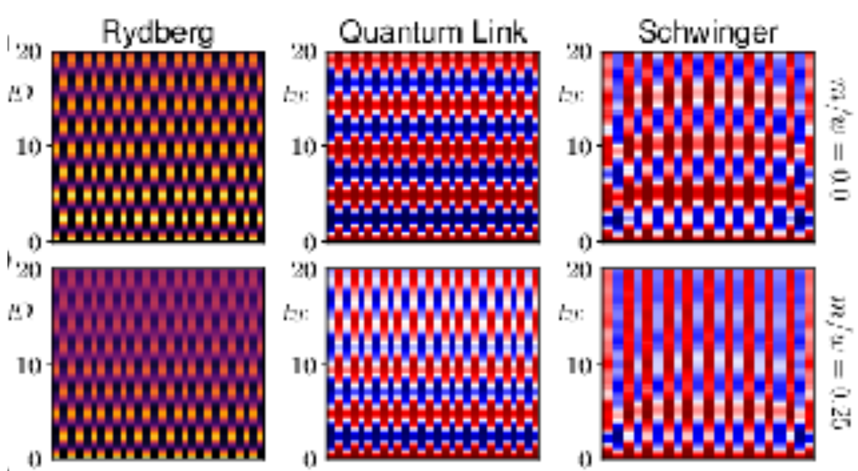


Rydberg atom arrays

Surace, …, AL et al. PRX (2020)

exact mapping

Rydberg-blockaded atomic array $\longleftrightarrow$ $U(1)$ LGT – Quantum Link Model $S = 1/2$



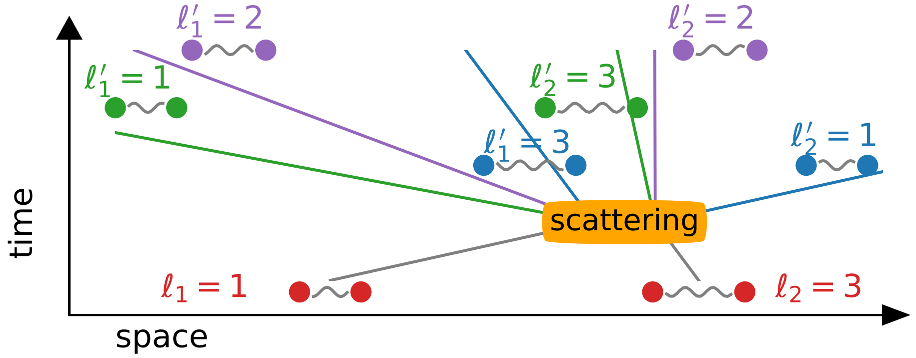
Experiment:
M. Lukin's group (Harvard)

Bernien et al. Nature (2017)

LGT interpretation of "quantum many-body scars"

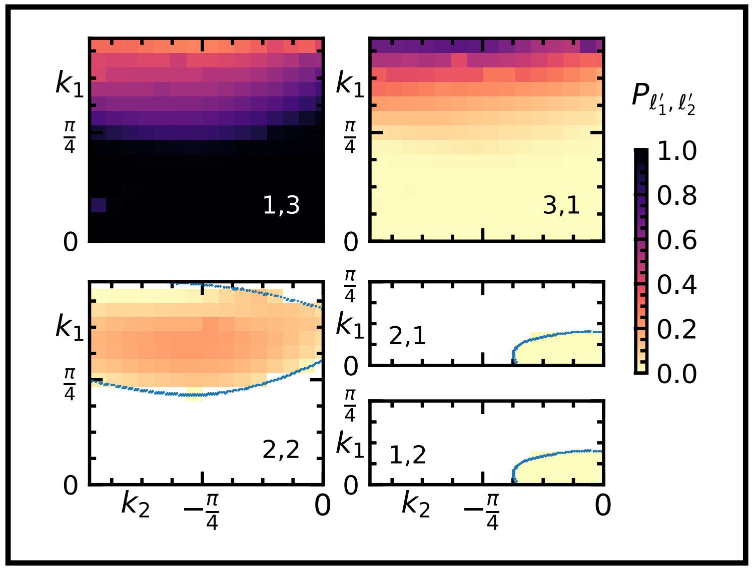
Meson collisions - I

Surace & AL
NJP (2021)



Meson-Meson collisions in $\mathbb{Z}_2$ LGT (~ Quantum Ising chain)

Exact solution of S-matrix for large fermion mass (benchmark)

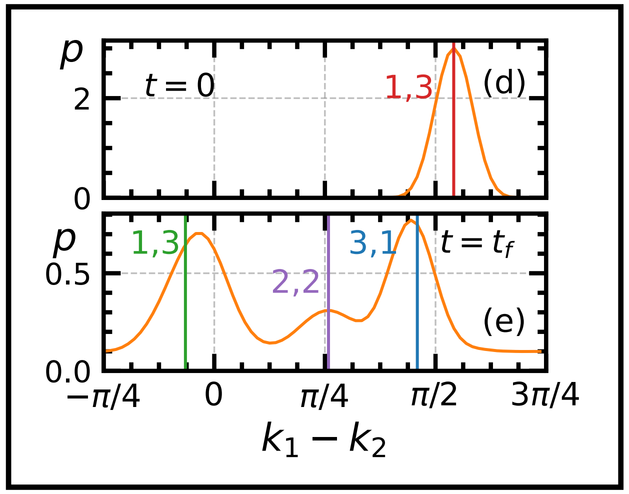


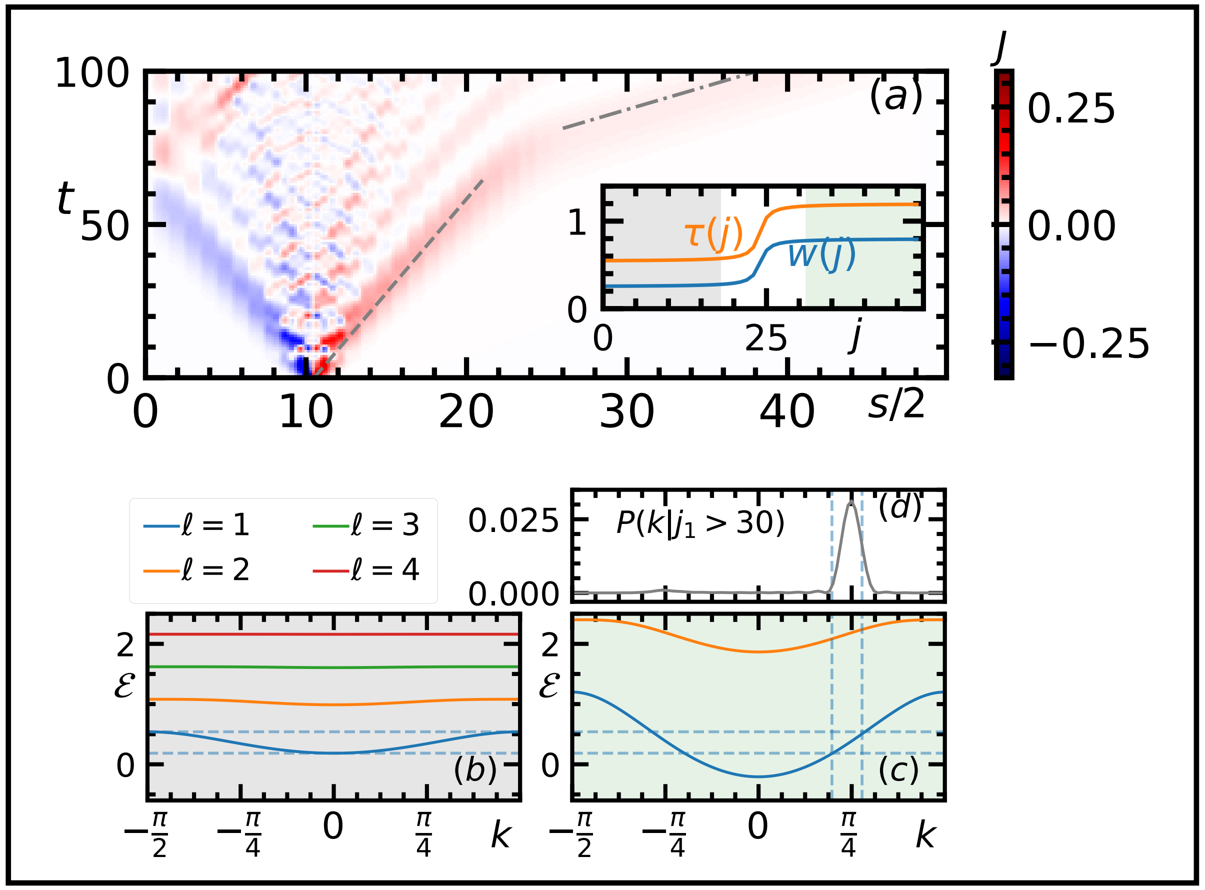
Protocol for quantum simulation:

✳ engineer LGT Hamiltonian ✓

✳ prepare incoming wavepackets

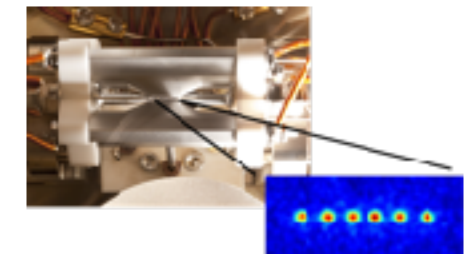
✳ measure S-matrix





Meson collisions - II

work in progress with:
E. Bennewitz, B. Ware, A. Schuckert, F. M. Surace,
A. Gorshkov, Z. Davoudi (theory)
& C. Monroe group (experiment)

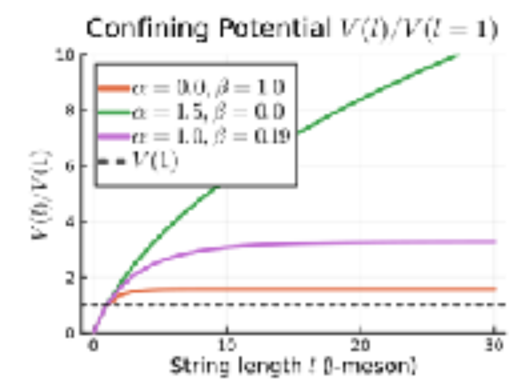


"Meson-Meson" collisions in variable-range Quantum Ising chain

$\longrightarrow$ analog quantum simulation with trapped ions

$$H = \sum_{i,j} J_0 \frac{e^{-\beta(r_{ij}-1)}}{r_{ij}^{\alpha}} X_i X_j + \sum_i h_i^{\infty} X_i + h_z \sum_i Z_i$$

tuneable α, β

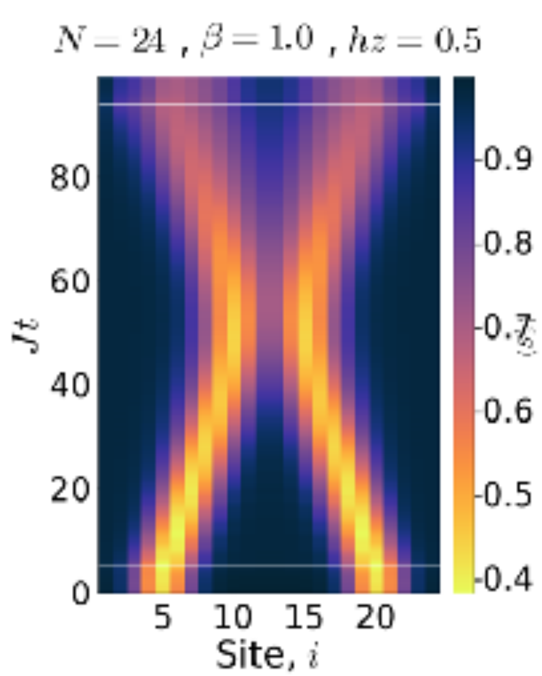


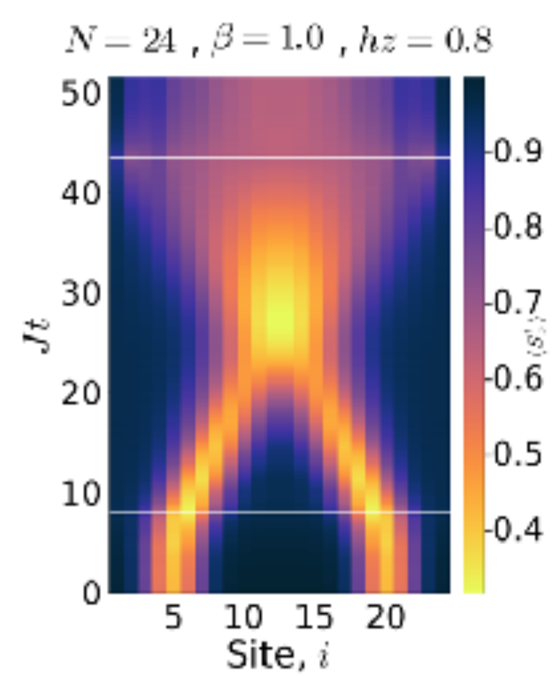
Main challenge: State preparation

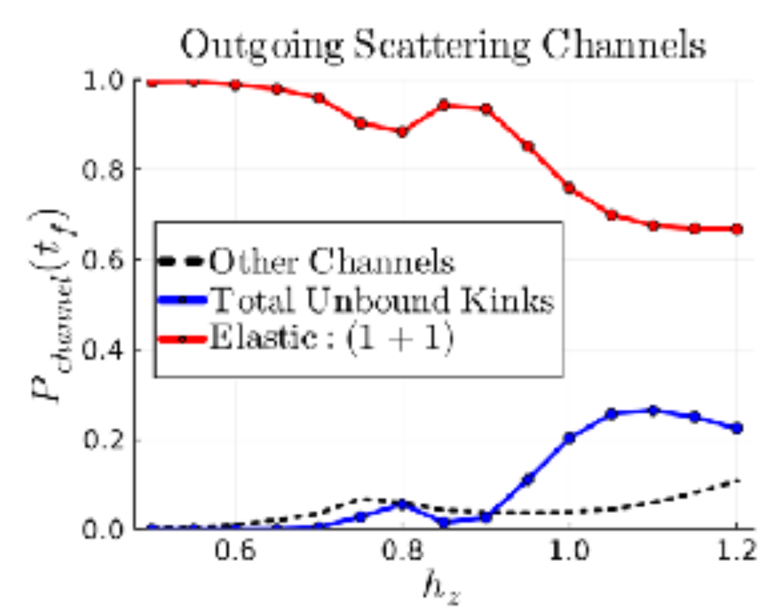
New key idea with native trapped-ion toolbox: Use phonon modes

Numerical simulations with realistic experimental parameters $|\psi_{\mathrm{final}}\rangle = U_{\mathrm{ramp}}^{\dagger} e^{-iHt} U_{\mathrm{ramp}} |\psi_0(x_1, k_1, x_2, k_2)\rangle$

preliminary results:







THANKS!

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