
# Advances in quantum simulation of lattice gauge theories: multiflavor models, fractional gauge fields, towards 2+1 D

QuantHEP, Munich August 5th, 2024


## Philipp Hauke

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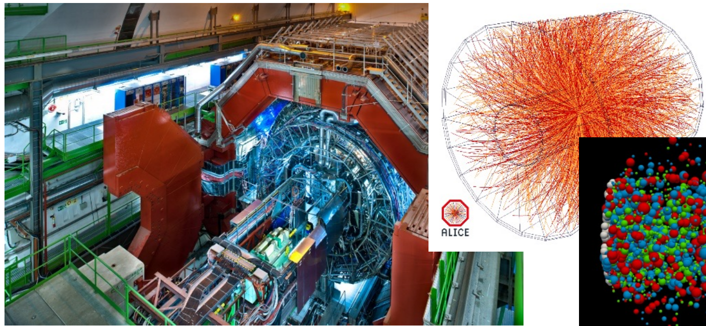
Funded by the European Union

# Lattice gauge theories – a corner stone of modern physics

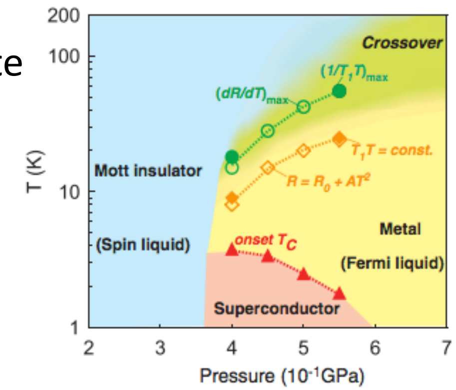
- Subatomic physics



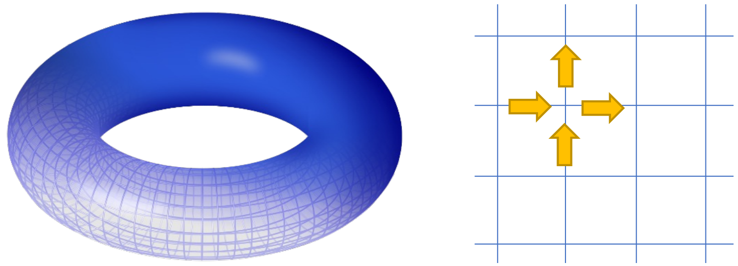
Alice detector @ CERN

Leonardo Supercomputer @ CINECA

- Solid-state physics




- Quantum-information processing



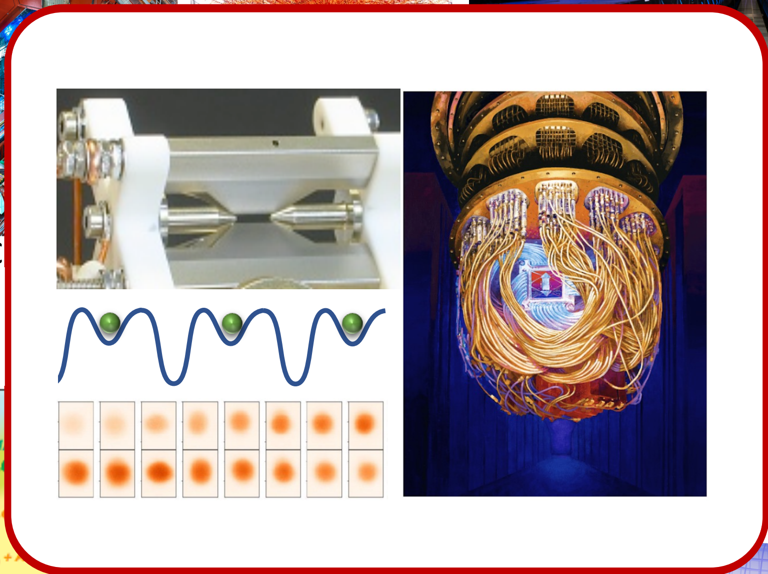
Topological quantum computing

# Lattice gauge theories – a corner stone of modern physics

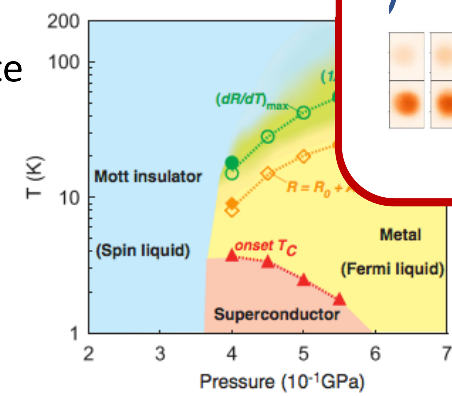
- Subatomic physics

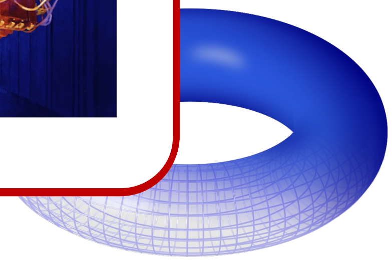
Alice detector @ C

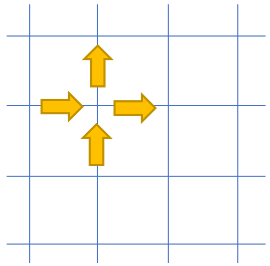
uter @ CINECA



- Solid-state physics



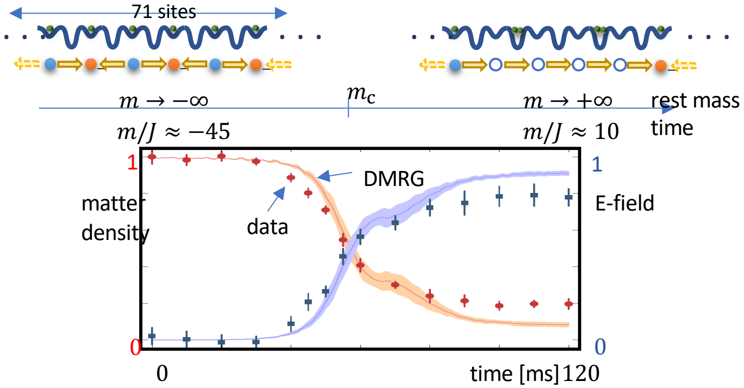


Topological quantum computing

# Many strides forward in quantum simulation of LGTs have been made

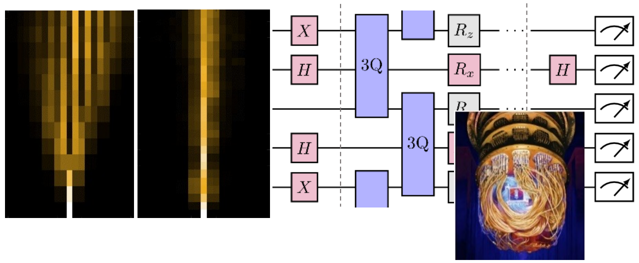
Reviews, e.g., Zohar, Cirac, Reznik, *RoPP* 2015; Dalmonte, Montangero, *Contemp. Phys.* 2016; Banuls et al., *EPJD* 2020; Aidelsburger et al., *Phil. Trans. R. Soc.* A 2022; Zohar, *Phil. Trans. R. Soc.* A 2022; Bauer, *PRX Quantum* 2023; *Di Meglio* et al., arXiv:2307.03236; Halimeh, Aidelsburger, Grusdt, Hauke, Yang, arXiv:2310.12201

Coleman's phase transition, thermalization, confinement in cold atoms




Yang, Sun, Ott, Wang, Zache, Halimeh, Yuan, Hauke, Pan, *Nature* 2020
Zhou, Su, Halimeh, Ott, Sun, Hauke, Yang, Yuan, Berges, Pan, *Science* 2022
Wei-Yong Zhang, et al., arXiv:2306.11794

Confinement in superconducting qubits




Mildenberger, Mruczkiewicz, Halimeh, Jiang, Hauke, arXiv:2203.08905
Halimeh, Lang, Mildenberger, Jiang, Hauke *PRX Quantum* 2021

Within Early Access Program by Google and Research Scholar Award ProGauge

Nice, but new challenge: proceed beyond single-flavor Abelian 1+1D


Pavel Popov


Paolo Stornati


Valentin Kasper


Erez Zohar


Maciej Lewenstein

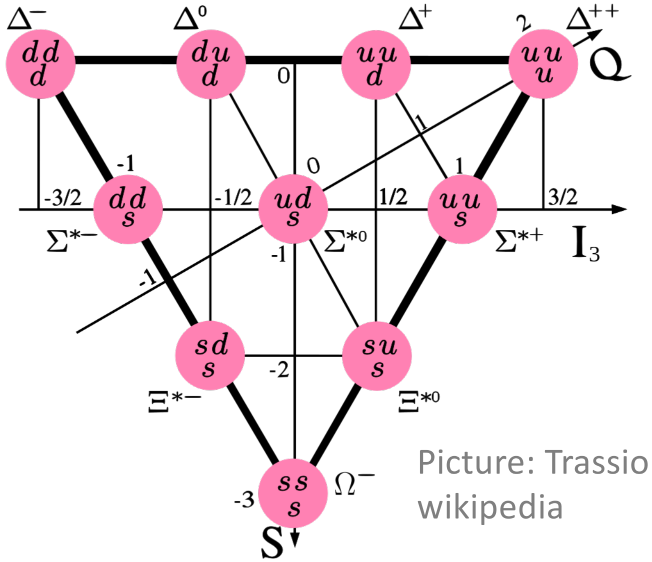
# Fractons in the multi-flavour Schwinger model

Pavel Popov, Valentin Kasper, Maciej Lewenstein, Erez Zohar,
Paolo Stornati, and Philipp Hauke, arXiv:2405.00745

# Multiflavor models hosts rich physics

Baryon decuplet

Isospin,
flavor symmetry



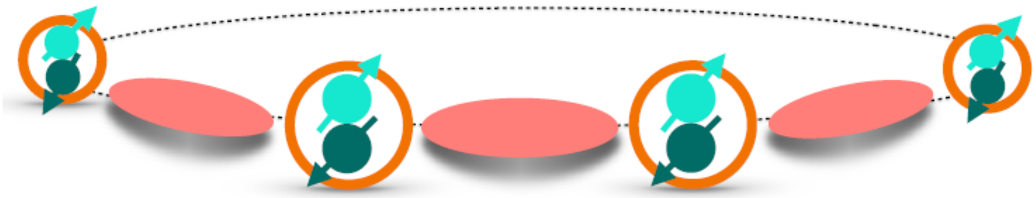

Picture: Trassiorf, wikipedia

*N*=3 severe sign problem

Non-trivial extension, but easier than colour

In context of quantum simulation & tensor networks, e.g., Funcke, Hartung, Jansen, Kühn, Pleinert, PoS LATTICE2022 (2023) 020,
Bañuls, Cichy, Cirac, Jansen, Kühn, Saito, arXiv:1611.00705

# Multiflavor-flavor Schwinger model



**Continuum**

$$H_{\text{QED}} = \sum_{\sigma=1}^{N_f} \int \mathrm{d}x \left[ \left( \overline{\psi}_{\sigma}^{\dagger}(x)\gamma_0\, i\gamma_1 \left(\partial_x + ie\hat{A}(x)\right) \overline{\psi}_{\sigma}(x) + \text{h.c.} \right) + m_{\sigma} \overline{\psi}_{\sigma}^{\dagger}(x)\gamma_0 \overline{\psi}_{\sigma}(x) + \frac{1}{2}\hat{E}(x)^2 \right]$$

Gauss' law $\quad \nabla E(x) - e \sum_{\sigma} \overline{\psi}_{\sigma}^{\dagger}(x)\gamma_0 \overline{\psi}_{\sigma}(x) = 0$

**Lattice**

$$H = J \sum_{\sigma=1}^{N_f} \sum_{x} (\hat{\psi}_{\sigma,x}^{\dagger} \hat{S}_{x,x+1}^{+} \hat{\psi}_{\sigma,x+1} + \text{h.c.}) + m_{\sigma} \sum_{x} (-1)^x \hat{\psi}_{\sigma,x}^{\dagger} \hat{\psi}_{\sigma,x} + g^2 \sum_{x} \left(S_{x,x+1}^{z}\right)^2$$

$$\frac{S_{i,i+1}^{z}}{2} - \frac{S_{i-1,i}^{z}}{2} - e \sum_{\sigma} \hat{\psi}_{\sigma,x}^{\dagger} \hat{\psi}_{\sigma,x} - \frac{1+(-1)^i}{2} = 0$$

(How much of the physics does the lattice model retain?)
(cutoff S, lattice spacing a)

# Multiflavor Schwinger model as prototype model for topological gauge-theory phenomena

Shifman, Smilga, PRD 1994

topological sectors

common lore: $\nu$ integer

SuSy Yang-Mills has non-zero gluino condensate $\langle \bar{\lambda}\lambda \rangle \neq 0$
($\lambda$= Majorana field, superpartner of gluon)

But: path-integral predicts (at small mass) $\langle \bar{\lambda}\lambda \rangle = -\partial_m \ln Z \Big|_{m=0}$

with $Z = \sum_\nu Z_\nu$

$Z_\nu = z_\nu \, m^{\nu \, N_c}$

thus $\langle \bar{\lambda}\lambda \rangle = 0$

How to reconcile? → need to admit for presence of **fractional topological sectors**

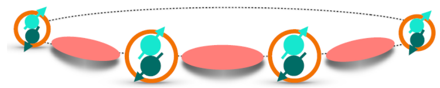
$$\langle \bar{\lambda}\lambda \rangle = -\lim_{m \to 0} \frac{z_{1/N_c}}{z_0}$$

**Can we probe such fractons in a simpler theory (and on a quantum simulator)?**

# Fractons in multiflavor Schwinger model

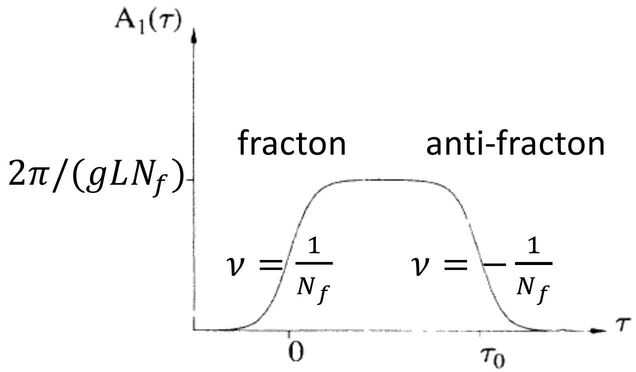
Shifman, Smilga, PRD 1994

Similarly, for $e^{ig\int A_1 dx} = \text{const},\ A_1$ defined up to different windings



# of windings of $A$ define topological Pontryagin charge $\nu_2 = \frac{e}{4\pi}\int d^2x \epsilon_{\mu\nu} F_{\mu\nu}$

Existence of fractional windings is known,
but usually they are confined




Topological charge:

$$\nu = \frac{gL}{2\pi}\int_{-\infty}^{\infty} \dot{A}_1 d\tau \quad = \quad \frac{gL}{2\pi}\left[A_1(\infty) - A_1(-\infty)\right] = 0.$$

How to reveal them?

# Fractional gauge fields through chiral condensate

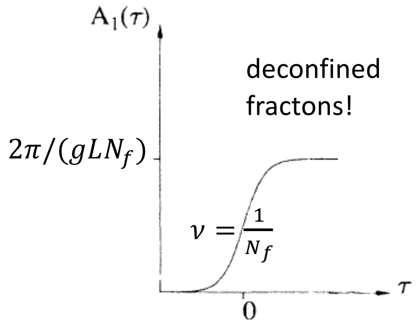
Shifman, Smilga, PRD 1994

Path-integral solution for chiral condensate $\langle\bar{\psi}\psi\rangle = -\partial_m \ln Z\Big|_{m=0}$ $\quad Z = \sum_\nu Z_\nu$ with $Z_\nu = z_\nu\, m^{2\nu}$

If $\nu$ only integer $\quad \langle\bar{\psi}\psi\rangle \xrightarrow[m\to 0]{} -\frac{z_1 m}{z_0}\Big|_{m=0} = 0$

(no individual fractional gauge-field configurations)

Conversely $\langle\bar{\psi}\psi\rangle \neq 0$ implies existence of $\nu = 1/2$ $\quad$ ( $\langle\bar{\psi}\psi\rangle \xrightarrow[m\to 0]{} -\frac{z_{1/2}}{z_0}$ )




Topological charge:

$$\nu = \frac{gL}{2\pi}\int_{-\infty}^{\infty} \dot{A}_1 d\tau = \frac{gL}{2\pi}\left[A_1(\infty) - A_1(-\infty)\right] = \frac{1}{N_f}$$

Do these fractons become relevant?

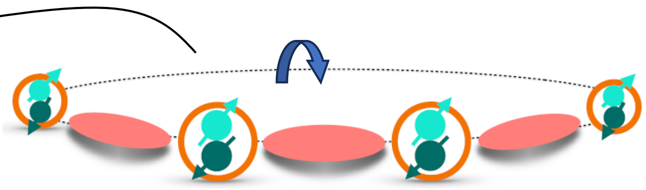
# Fracton field configurations become visible in chiral condensate

Popov, Kasper, Lewenstein, Zohar, Stornati, and Hauke, arXiv:2405.00745

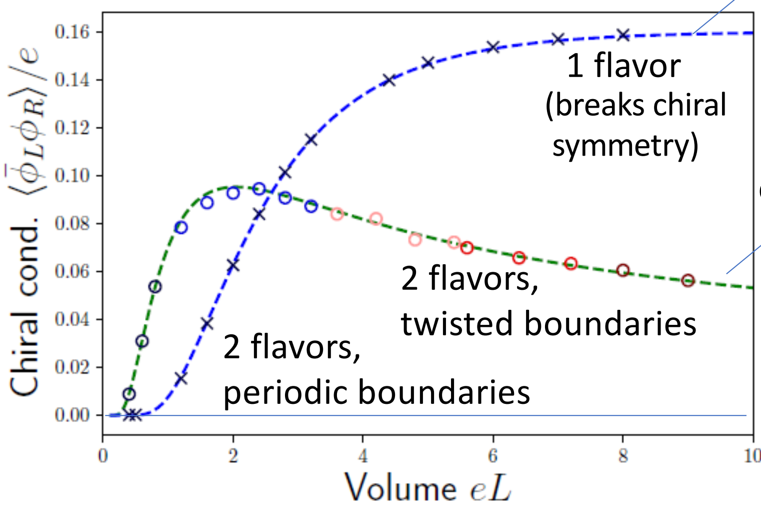
flavor twisted boundary conditions

"torons" $\psi(x = L) = \psi(x = 0)$,
$\chi(x = L) = -\chi(x = 0)$

breaks chiral symmetry



continuum




continuum

Shifman, Smilga, PRD 1994

$$\frac{1}{NL} \exp\left\{ -\frac{\pi}{N\mu L} \right\} \qquad \mu^2 = Ng^2/\pi$$

(at small $L$)

Note: in QED (in contrast to SuSy YM) finite volume effect (but slow algebraic decrease)

Formulated positively: Finite volume reveals fractons

→ drastically different behavior for 1-flavor and 2-flavor model!

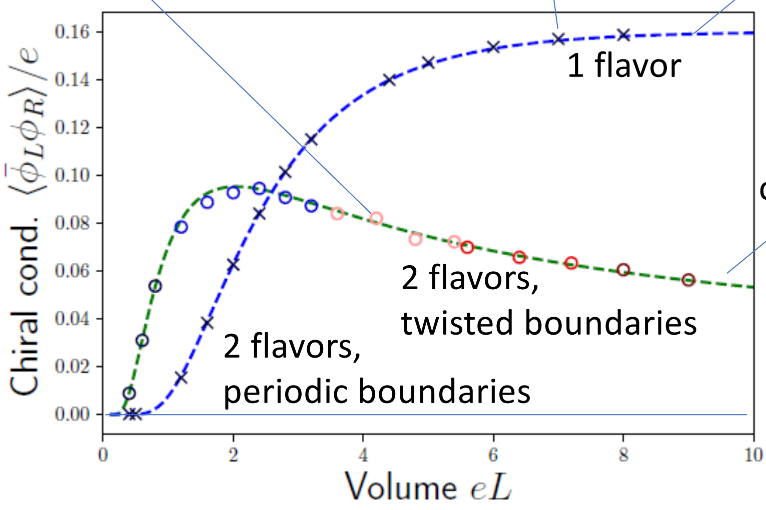
# Can we probe that on a quantum simulator?

Popov, Kasper, Lewenstein, Zohar, Stornati, and Hauke, arXiv:2405.00745

numerics
$a = 0.1 - 0.5, m = 0$
E-field cutoff $= \pm 3$

numerics
E-field cutoff $= \pm 3, a = 0.05 - 0.5, m = -1/4$

continuum




Shifman, Smilga, PRD 1994

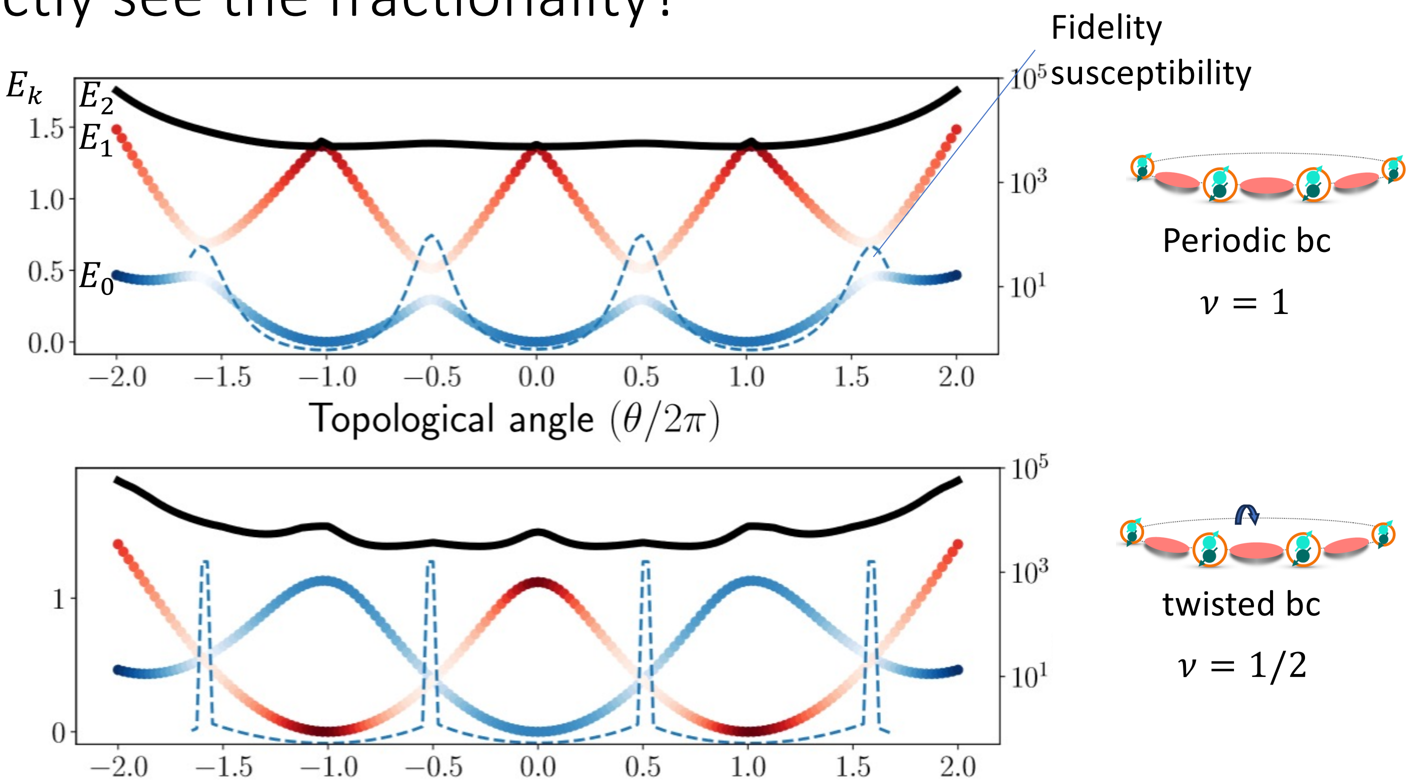
$$\frac{1}{NL} \exp\left\{-\frac{\pi}{N\mu L}\right\} \qquad \mu^2 = Ng^2/\pi$$

visible already in very coarse and highly truncated system!
→ perfect playground for
quantum simulators!

# Can we directly see the fractionality?

$$Z = \sum_{\nu} e^{i\nu\theta} Z_{\nu}$$

Periodic under
$\theta \to \theta + 2\pi/\nu$




Lattice result
$L = (4\,\text{sites} + 4\,\text{links})$
$S = 2, ea = 1$
$\frac{m}{e} = 0.4$

- Consistent with small $m$ continuum prediction Misumi, Tanizaki, Ünsal, JHEP 2019

$$E_k(\theta) = -2m \exp\left(-\frac{\pi}{N\mu eL}\right)\cos\left(\frac{\theta + 2\pi k}{N}\right)$$

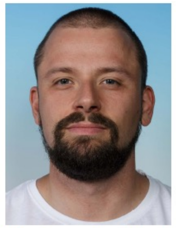
- **Physics retained, even in non-pertubative regime** $(\frac{m}{e} \sim 1)$
- **Small sizes and cutoffs ideal for quantum simulators!**

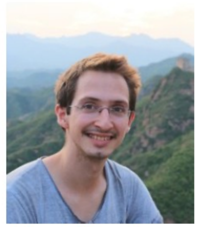

Pavel Popov


Valentin Kasper


Erez Zohar


Maciej Lewenstein


Michael Meth


Martin Ringbauer

# Implementing gauge theories with qudits

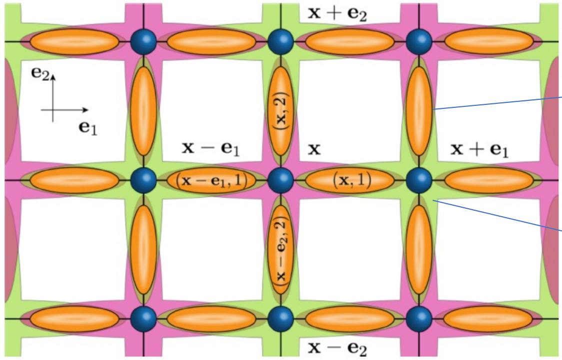
Pavel P Popov, Meth, Lewenstein, Hauke, Ringbauer, Zohar, Kasper,

Phys. Rev. Research 6, 013202 (2024)

Starting point: Qudits with cold atoms Kasper, González-Cuadra, Hegde, Xia, Dauphin, Huber, Tiemann, Lewenstein, Jendrzejewski, Hauke, Quantum Sci. Technol. 7 015008 (2022)

For LGTs, see also, e.g., González-Cuadra, Zache, Carrasco, Kraus, Zoller, Phys. Rev. Lett. 129, 160501 (2022)

# Lattice gauge theories require lots of degrees of freedom

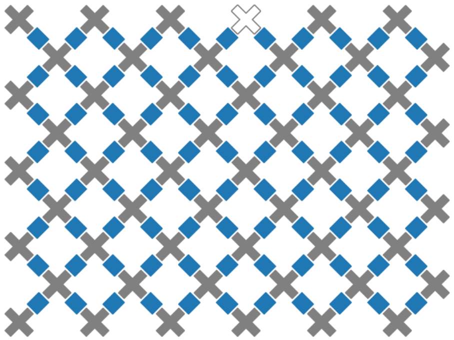



gauge-field (from −cutoff to +cutoff)

matter

could have
- spin
- particle/antiparticle
- Flavour
- colour

But: quantum computers are (conventionally) lattices of qubits



Google Quantum AI

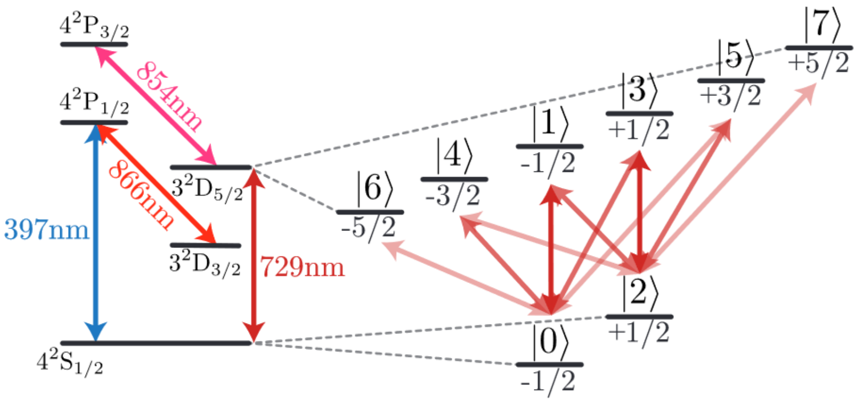
Solution 1: find minimal models that contain interesting physics

Solution 2: go analog and use additional degrees of freedom

Solution 3: compress quantum information

# New development in quantum computing: qu*d*it systems are now available

$^{40}Ca^{+}$ ions: 7 levels free for universal computation




*A universal qudit quantum processor with trapped ions*
Ringbauer, Meth, Postler, Stricker, Blatt, Schindler, Monz
Nature Physics 18, 1053 (2022)

Note: qdits developed also, e.g., for SC circuits, Rydbergs, …

Also for quantum optimization, e.g.:
Deller, Schmitt, Lewenstein, Lenk, Federer, Jendrzejewski, Hauke, Kasper, PRA, 2023; Garcia de Andoin, Bottarelli, Schmitt, Oregi, Hauke, Sanz, arXiv:2306.04414 (2023)

# Our model system: Abelian 2+1D

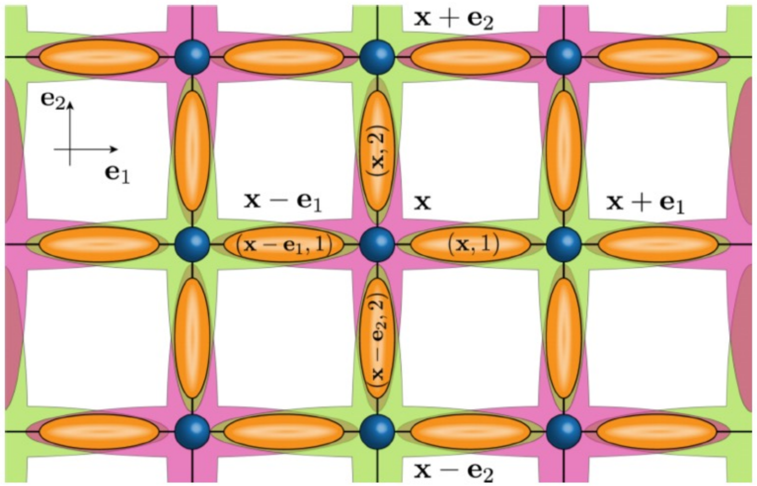
$E_{x,i}$: (from −cutoff to +cutoff)

$$H_G = \frac{g^2}{2}\sum_{\mathbf{x},i} E_{\mathbf{x},i}^2 + \frac{1}{2g^2}\sum_{\mathbf{p}}\left[U_{\mathbf{p}} + U_{\mathbf{p}}^\dagger\right]$$

$$U_{\mathbf{p}} = U_{\mathbf{x},1}U_{\mathbf{x}+\mathbf{e}_1,2}U_{\mathbf{x}+\mathbf{e}_2,1}^\dagger U_{\mathbf{x},2}^\dagger$$

$$H_M = M\sum_{\mathbf{x}}(-1)^{s_\mathbf{x}}\psi_\mathbf{x}^\dagger\psi_\mathbf{x}$$

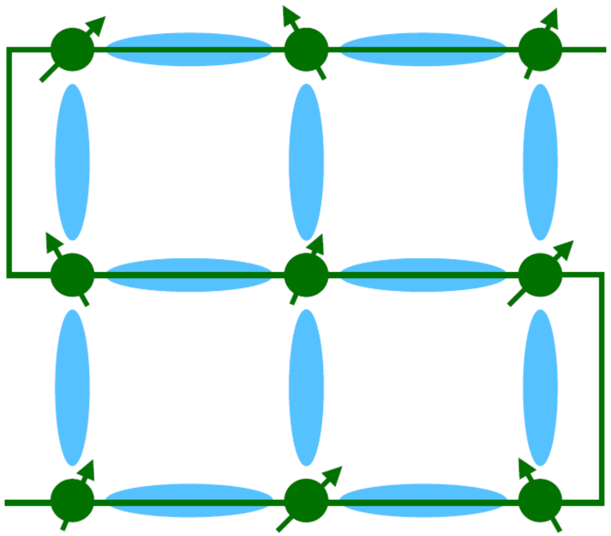
$$H_{\mathrm{GM}} = \frac{1}{2}\sum_{\mathbf{x},i}\left[i\psi_\mathbf{x}^\dagger U_{\mathbf{x},i}\psi_{\mathbf{x}+\mathbf{e}_i} + h.c.\right]$$




$$G_\mathbf{x} = \sum_i\left[E_{\mathbf{x},i} - E_{\mathbf{x}-\mathbf{e}_i,i}\right] - \psi_\mathbf{x}^\dagger\psi_\mathbf{x} + \underbrace{\frac{1}{2}[1-(-1)^\mathbf{x}]}_{=:s_\mathbf{x}}$$

$$G_\mathbf{x}|\psi\rangle = 0\ \forall\mathbf{x}$$

# Challenge for quantum simulation in 2+1D: fermionic statistics



**Problem:** Jordan-Wigner strings do not vanish in higher spatial dimensions → highly non-local interactions

**Solution:** Absorb fermionic statistics into gauge fields
E. Zohar and JI. Cirac, Physical Review B 98 (7), 075119 (2018)

→ introduce hard-core bosons $\eta_x$, plus auxiliary fields

… some unitary transformations later
Popov, Meth, Lewenstein, Hauke, Ringbauer, Zohar, Kasper, PRR 2024

# Unitarily equivalent theory

$$H = \frac{g^2}{2}\sum_{\mathbf{x},i} E_{\mathbf{x},i}^2 - \frac{1}{2g^2}\sum_{\mathbf{p}}\left[\tilde{U}_{\mathbf{p}} + \tilde{U}_{\mathbf{p}}^\dagger\right] + M\sum_{\mathbf{x}}(-1)^{s_{\mathbf{x}}}\eta_{\mathbf{x}}^\dagger\eta_{\mathbf{x}} + \frac{1}{2}\sum_{\mathbf{x},i}\left(f_{\mathbf{x},i}(E_{\cdot,\cdot})\eta_{\mathbf{x}}^\dagger U_{\mathbf{x},i}\eta_{\mathbf{x}+\mathbf{e_i}} + \text{h.c.}\right)$$

$$\tilde{U}_{\mathbf{p}} = \exp[i\pi(E_{\mathbf{x},1} + E_{\mathbf{x}+\mathbf{e}_1,2} + E_{\mathbf{x}+\mathbf{e}_2,2} + E_{\mathbf{x}+\mathbf{e_2}-\mathbf{e_1},1})]U_{\mathbf{x},1}U_{\mathbf{x}+\mathbf{e}_1,2}U_{\mathbf{x}+\mathbf{e}_2,1}^\dagger U_{\mathbf{x},2}^\dagger$$

In 2+1D $\quad f_{\mathbf{x},1}(E_{\cdot,\cdot}) = (-1)^{E_{\mathbf{x}+\mathbf{e_1},1}+E_{\mathbf{x}+\mathbf{e_1},2}}\,;\; f_{\mathbf{x},2}(E_{\cdot,\cdot}) = (-1)^{E_{\mathbf{x},1}+E_{\mathbf{x}-\mathbf{e_1}+\mathbf{e_2},1}+E_{\mathbf{x}+\mathbf{e_2},2}+E_{\mathbf{x}+\mathbf{e_2},1}}$

In 1+1D $\quad f_{\mathbf{x}}(E_{\cdot,\cdot}) = (-1)^{E_{\mathbf{x}+\mathbf{1}}}$

Local theory

Perfectly fine gauge theory

Fulfils the Gauss' law for the bosons $\quad G_{\mathbf{x}} = \sum_i \left[E_{\mathbf{x},i} - E_{\mathbf{x}-\mathbf{e}_i,i}\right] - \eta_{\mathbf{x}}^\dagger\eta_{\mathbf{x}} + s_{\mathbf{x}}$

Unitarily equivalent to original theory

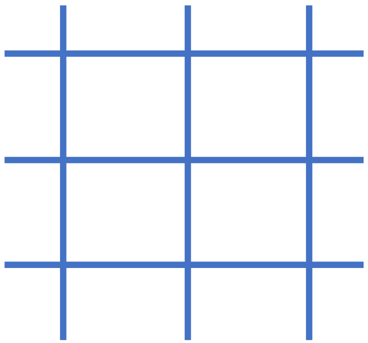
# Further reduce degrees of freedom: integrate out matter fields

Note: in 1+1D can integrate out gauge fields

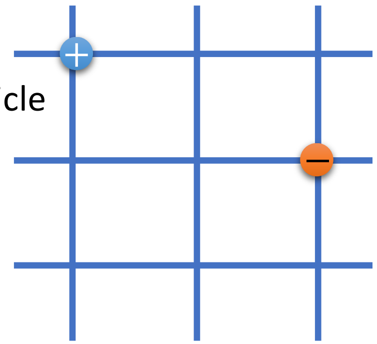
$$E_x = E_{x-1} + n_x + s_x$$

In 2+1D: charges do no longer uniquely define gauge fields

vacuum



Particle-antiparticle



# Further reduce degrees of freedom: integrate out matter fields

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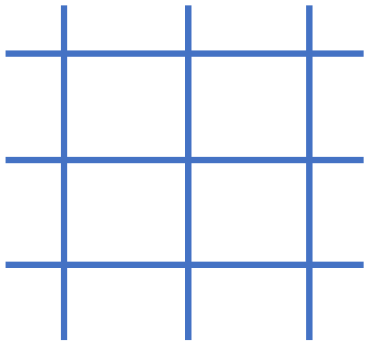
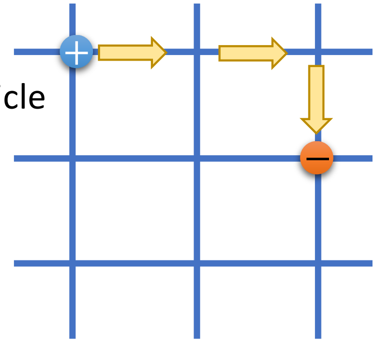
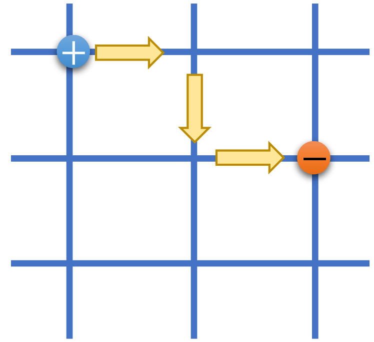


Particle-antiparticle



or



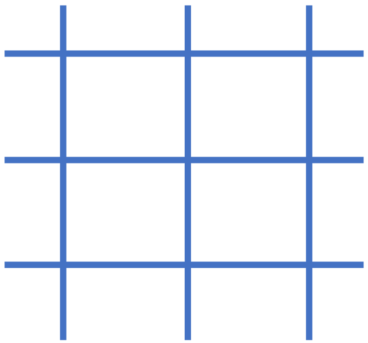
?

# Further reduce degrees of freedom: integrate out matter fields

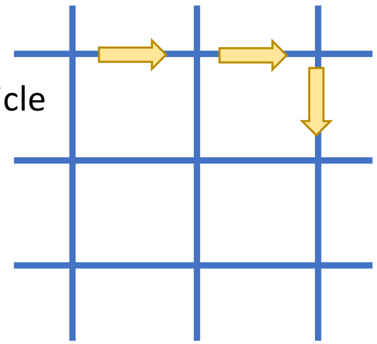
But: gauge fields uniquely define charges

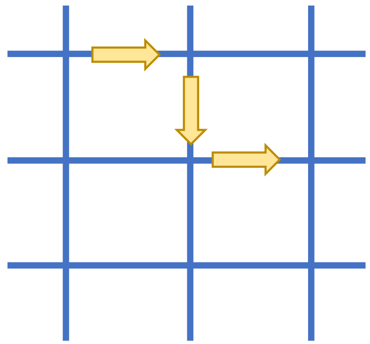
$$n_x = E_x - E_{x-1} - s_x$$

vacuum



Particle-antiparticle





Continuity: what goes in comes out

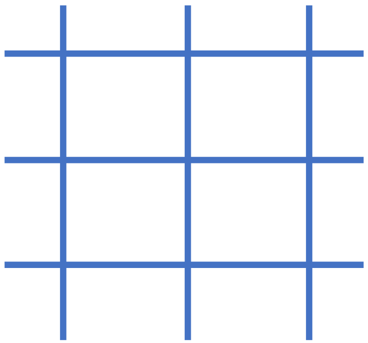
⇒ no charges present

# Further reduce degrees of freedom: integrate out matter fields

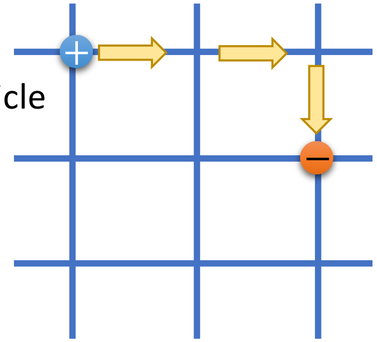
But: gauge fields uniquely define charges

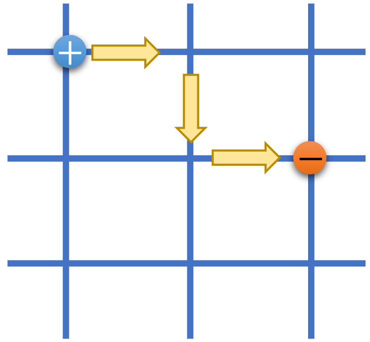
$$n_x = E_x - E_{x-1} - s_x$$

vacuum



Particle-antiparticle





Continuity: what goes in comes out

⇒ no charges present

⇒ two charges present

# Use this to remove charges from game

Unitary transformation $\mathscr{U} = \prod_{\mathbf{x}} (\eta_{\mathbf{x}} + \eta_{\mathbf{x}}^{\dagger})^{g_{\mathbf{x}}}$ Physical states $|\tilde{\psi}\rangle = \mathscr{U}\,|\psi\rangle$ obey $\eta_{\mathbf{x}}^{\dagger}\eta_{\mathbf{x}}\,|\tilde{\psi}\rangle = 0$

2+1D

$$H = \frac{g^2}{2}\sum_{\mathbf{x},i} E_{\mathbf{x},i}^2 - \frac{1}{2g^2}\sum_{\mathbf{p}}\left[\tilde{U}_{\mathbf{p}} + \tilde{U}_{\mathbf{p}}^{\dagger}\right] + 2M\sum_{\mathbf{x},i}(-1)^{\mathbf{x}}E_{\mathbf{x},i}$$
$$+\frac{1}{2}\sum_{x}\left(P_{1,\boldsymbol{x}}(-1)^{E_{x,1}+E_{x+\mathbf{e_1}-\mathbf{e_2},2}-s_{x+\mathbf{e_1}}}U_{\boldsymbol{x},1}P_{1,\boldsymbol{x}+\boldsymbol{e}_1} - P_{1,\boldsymbol{x}}(-1)^{E_{x,1}+E_{x,2}-s_{x+\mathbf{e_2}}}U_{\boldsymbol{x},2}P_{1,\boldsymbol{x}+\boldsymbol{e}_2} + \text{h.c.}\right)$$

1+1D

$$H = \frac{g^2}{2}\sum_{\mathbf{x}} E_{\mathbf{x}}^2 + 2M\sum_{\mathbf{x}}(-1)^{\mathbf{x}}E_{\mathbf{x}} + \sum_{\mathbf{x}}\left[P_{1,\mathbf{x}}(-1)^{E_{\mathbf{x}+1}}U_{\mathbf{x}}P_{1,\mathbf{x}+1} + \text{h.c.}\right]$$

$P_{1,\boldsymbol{x}}$: projector onto E-field configurations corresponding to physical subspace

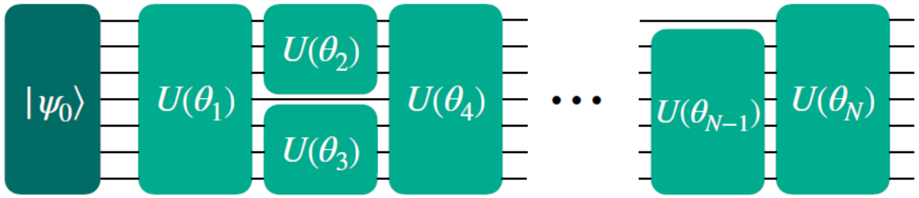
flips E-field
But is only allowed to do so, if underlying is the correct charge configuration!
(in 1+1D: "complicated way to get PXP Hamiltonian")

Bernien et al.,
Surace et al., etc

Result: local Hamiltonian of only gauge fields,
values from –cutoff to +cutoff → qudits!

# Since interactions look complicated, we look at a variational algorithm

Trial state of the form $|\psi(\boldsymbol{\theta})\rangle = U_N\left(\theta_N\right)\cdots U_k\left(\theta_k\right)\cdots U_1\left(\theta_1\right)|\psi_0\rangle$




Evolution within variational manifold:
Evolution equation for $|\psi(t)\rangle$ is traded for evolution equation for $\boldsymbol{\theta}(t)$

$$\sum_\nu M_{\mu\nu}\dot{\theta}_\nu(t) = V_\mu$$

$$M_{\mu\nu}(\boldsymbol{\theta}) = \mathrm{Tr}\left[\frac{\partial\rho}{\partial\theta_\mu}\frac{\partial\rho}{\partial\theta_\nu}\right] \text{ and } V_\mu(\boldsymbol{\theta}) = \mathrm{Tr}\left[\frac{\partial\rho}{\partial\theta_\mu}\mathscr{L}[\rho]\right]$$

$$\rho(\boldsymbol{\theta}) := |\psi(\boldsymbol{\theta})\rangle\langle\psi(\boldsymbol{\theta})|$$

# Execution of the variational algorithm

Initialize $|\psi_0\rangle$

Apply the quantum circuit for $\boldsymbol{\theta}(t)$

Measure the quantities $M_{\mu\nu}\left(\boldsymbol{\theta}(t)\right)$ and $V_\mu\left(\boldsymbol{\theta}(t)\right)$

Measure energy $\langle H\rangle_{\boldsymbol{\theta}(t)}$

Measure obs. $\langle \mathcal{O}\rangle_{\boldsymbol{\theta}(t)}$

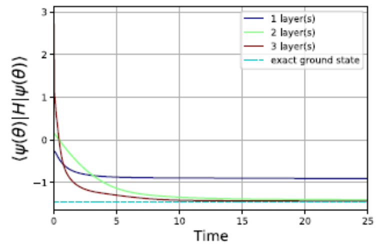
Solve

$$\sum_\nu M_{\mu\nu}(t)[\theta_\nu(t+\Delta t)-\theta_\nu(t)] = V_\mu(t)\Delta t$$

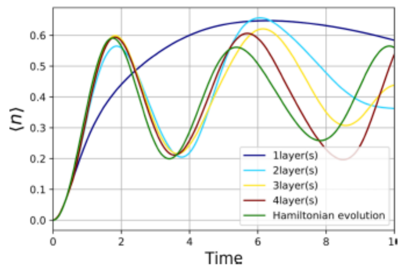
for $\boldsymbol{\theta}(t+\Delta t)$ numerically

Feed in the parameters $\boldsymbol{\theta}(t+\Delta t)$.

**Imaginary-time evolution**



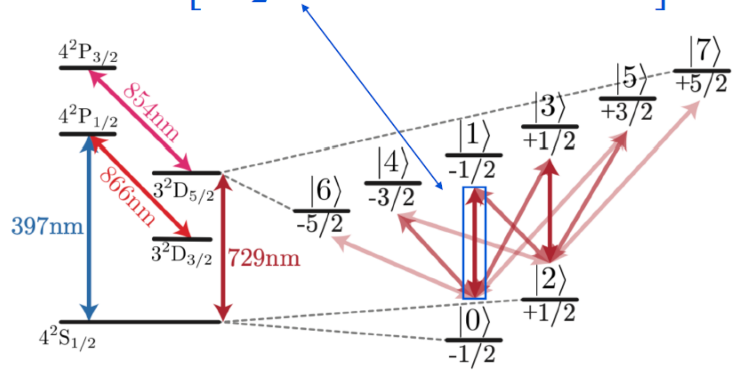

**Real-time evolution**



# Use elementary operations in trapped ion qudits

- Orthonormal basis of a qudit: $\{\,|0\rangle, |1\rangle, \cdots, |d-1\rangle\}$ .
- Single qudit operations - $d \times d$ unitary matrices; $d^2 - 1$ different single qudit operations, e.g. $R^{i,j}(\theta, \varphi)$.
- For universality - single qudit operations + entangling operation, e.g. Mølmer-Sørensen gate $MS^{i,j}(\theta, \varphi)$, needed.

$$R^{0,1}(\theta,\varphi) = \exp\left[-\frac{i\theta}{2}\left(\cos(\varphi)\sigma_X^{0,1} + \sin(\varphi)\sigma_Y^{0,1}\right)\right]$$



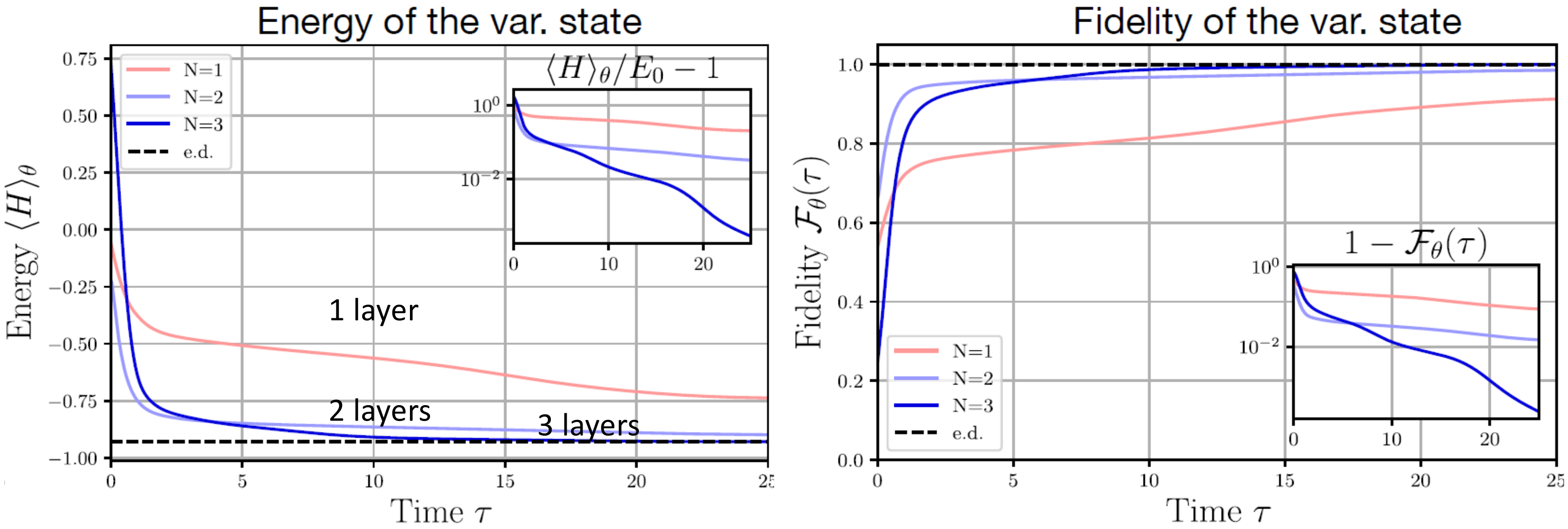

$$MS^{i,j}(\theta,\varphi) = \exp\left[-\frac{i\theta}{4}(\sigma_\varphi^{i,j} \otimes \mathbb{1} + \mathbb{1} \otimes \sigma_\varphi^{i,j})^2\right]$$

Pavel P Popov, Meth, Lewenstein, Hauke, Ringbauer, Zohar, Kasper
arXiv:2307.15173; PRR 2024

# Numerical benchmarks

2+1D, 4 qutrits in a plaquette; for each layer, 4 MS gates.

Imaginary time

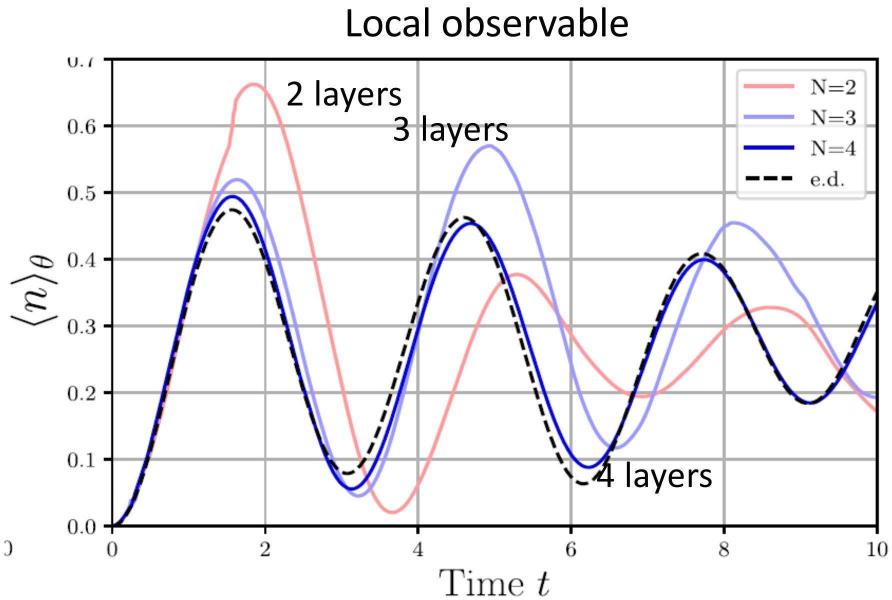


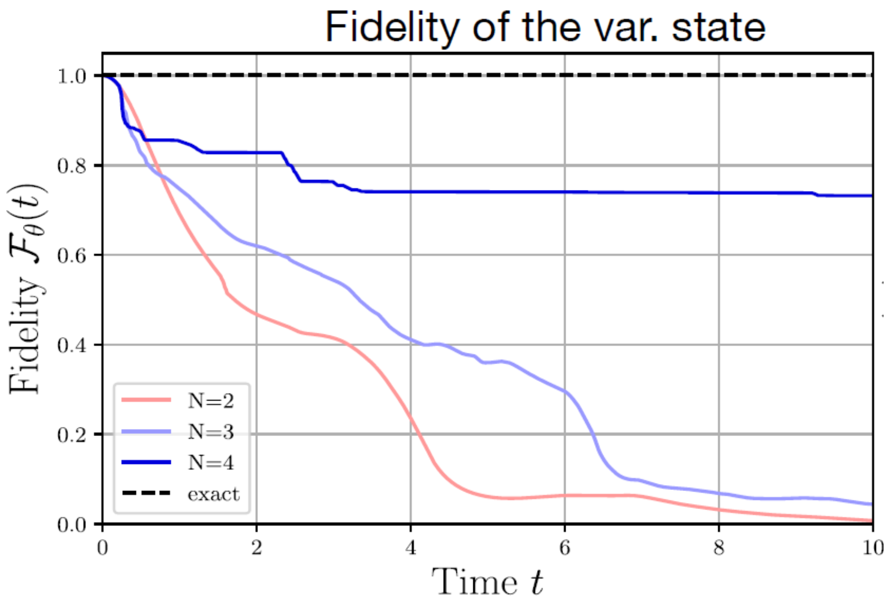

Pavel P Popov, Meth, Lewenstein, Hauke, Ringbauer, Zohar, Kasper
arXiv:2307.15173; PRR 2024

# Numerical benchmarks

2+1D, 4 qutrits in a plaquette; for each layer, 4 MS gates.

Real time




Pavel P Popov, Meth, Lewenstein, Hauke, Ringbauer, Zohar, Kasper
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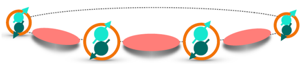
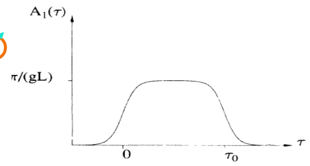
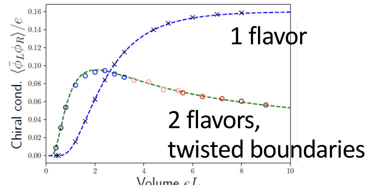
# Conclusions

# Take away messages

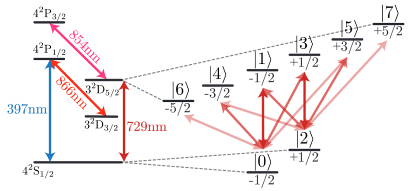
Fascinating target within reach: fracton excitations

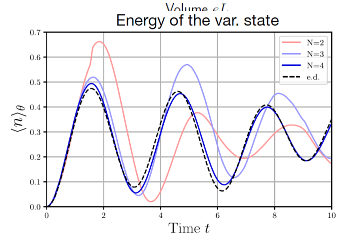




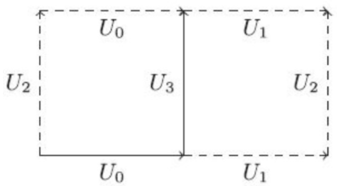



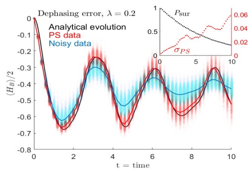

Qudits open new ways for efficient quantum simulation, also in dimensions higher than 1+1D and for multiple flavors



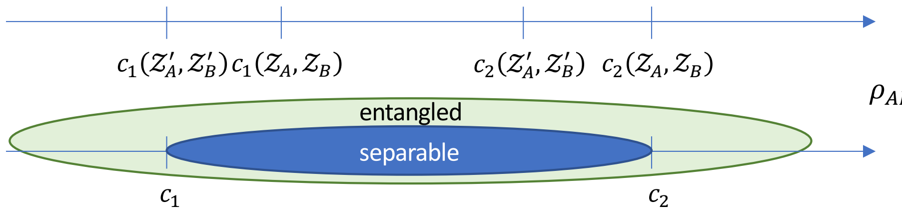



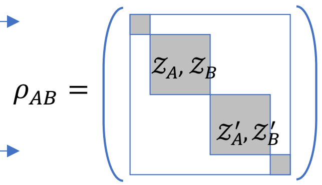

Ongoing work: extensions to non-Abelian




Quantum simulators open ways for new observables: witness entanglement
Panizza, Costa de Almeida, Hauke, JHEP 2022



Team members involved (left to right) Veronica Panizza, Julius Mildenberger, Edoardo Ballini, Emanuele Tirrito, Matteo Wauters.

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Pavel Popov, Paolo Stornati, Maciej Lewenstein, Valentin Kasper, Jad Halimeh, Bing Yang, Zhen-Sheng Yuan, Jian-Wei Pan, Erez Zohar, Fabian Grusdt, Monika Aidelsburger, Google Quantum AI, . . .

Thank you!

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