Probing confinement and gauge symmetry on a quantum computer

Kitzbühel Humboldt Kolleg

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Thanks to:
ERC Starting Grant *StrEnQTh* (project ID 804305)
Google Research Scholar Award *ProGauge*

Quantum computers are at a decisive stage

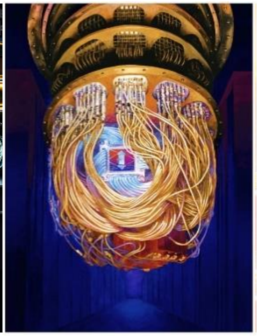
PAST — TODAY — FUTURE

experiments

Blatt group, Innsbruck

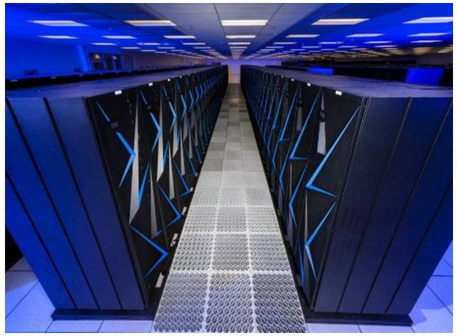
first prototypes

AQT



Google

Universal, scalable, error-corrected quantum computer



CINECA

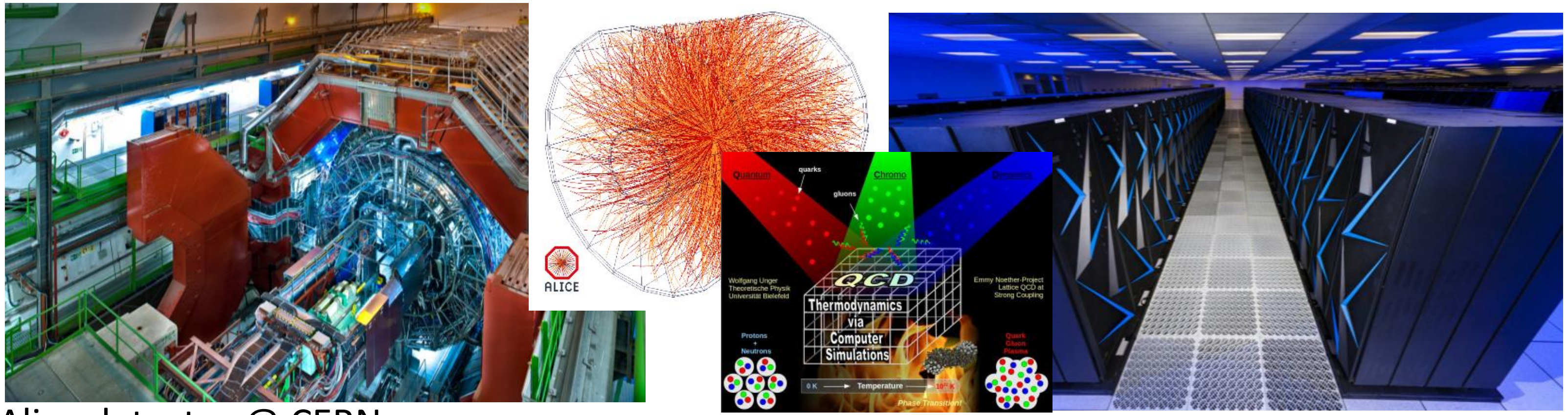
How to push forward?

- Need intermediate milestones (efficient algorithms for problems of practical relevance)
- Hardware agnostic approach not yet best performant

→ requires effort across disciplines, involving theory, experiment, engineering, and end users

Lattice gauge theories – excellent use case

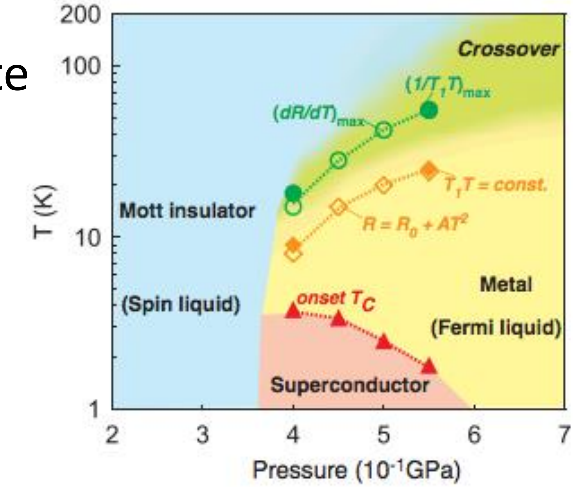
- Subatomic physics



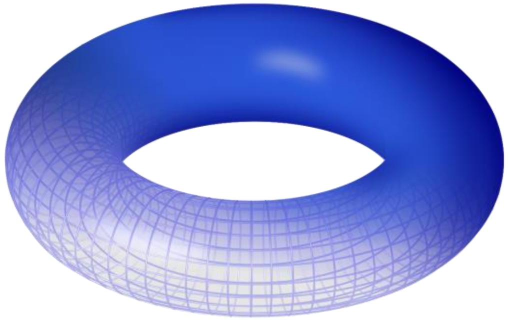
Alice detector @ CERN

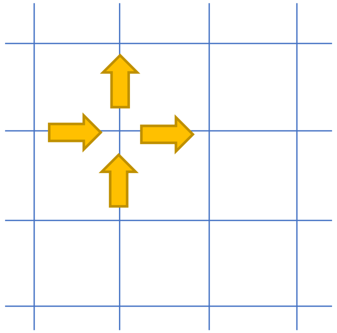
Leonardo Supercomputer @ CINECA

- Solid-state physics



- Quantum-information processing





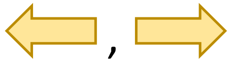
Pictures: Alice collaboration; Cineca; W. Unger, Universität Bielefeld;

Key challenge –
local conservation law = gauge invariance

e.g., U(1) symmetry: $\rho(x) = \nabla E(x)$ (Gauss' law of QED)

minimal lattice model:

$\tau_{i-1,i}$ $\psi_i, \psi_i^\dagger, n_i$ $\tau_{i,i+1}$

$\tau^z_{i,i+1} \in \{|0\rangle, |1\rangle\}$ $\leftrightarrow$ E-field 

 $\leftrightarrow$ 

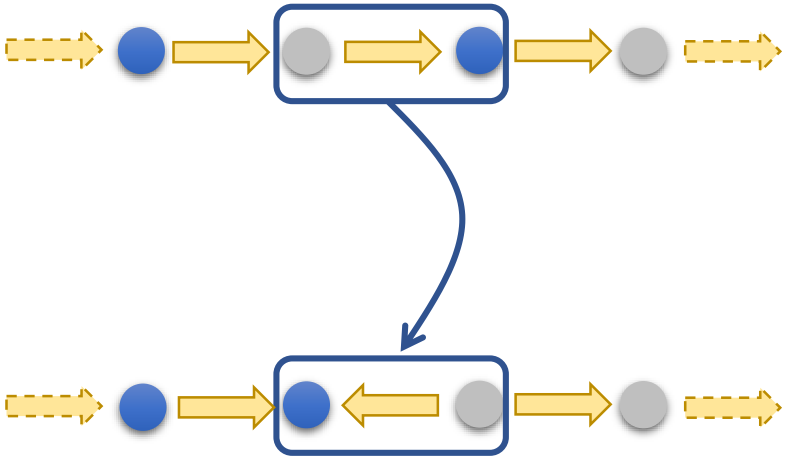
Quantum link model, e.g., Uwe-Jens Wiese, *Annalen der Physik* 2013

$$G_i = n_i - \frac{\tau^z_{i,i+1}}{2} + \frac{\tau^z_{i-1,i}}{2} + \frac{1+(-1)^i}{2} \coloneqq 0 \qquad [G_i, H] = 0$$

Key process: gauge invariant hopping

$$H = J\sum_i(\psi_i^\dagger\, \tau_{i,i+1}^{+}\psi_{i+1} + \mathrm{h.c.})$$

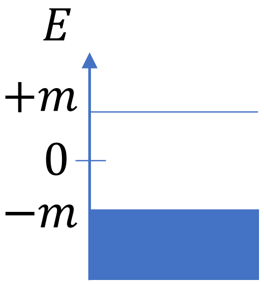
$$G_i = n_i - \frac{\tau_{i,i+1}^{z}}{2} + \frac{\tau_{i-1,i}^{z}}{2} + \frac{1+(-1)^i}{2}$$

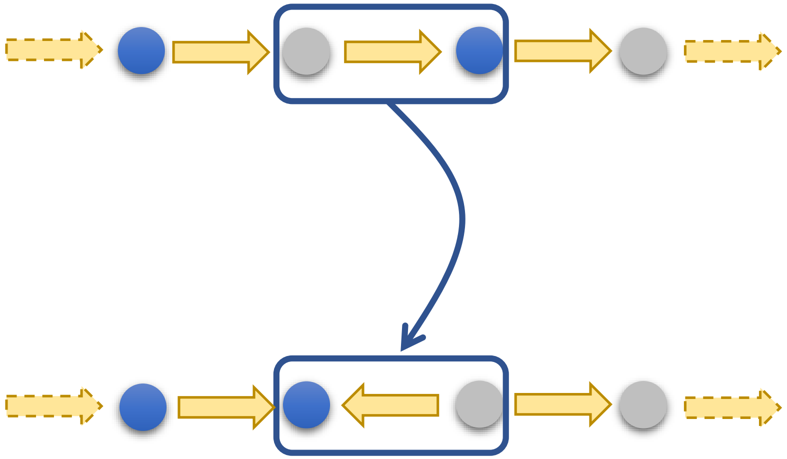


Simplified toy model of QED

"staggered fermions"
Kogut, Susskind, *Phys. Rev. D* 1975

$$H = J\sum_i(\psi_i^\dagger \tau_{i,i+1}^{+}\psi_{i+1} + \mathrm{h.c.}) + m\sum_i(-1)^i\psi_i^\dagger\psi_i \qquad G_i = n_i - \frac{\tau_{i,i+1}^{z}}{2} + \frac{\tau_{i-1,i}^{z}}{2} + \frac{1+(-1)^i}{2}$$





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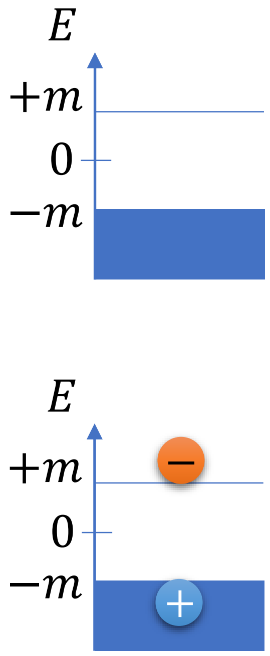
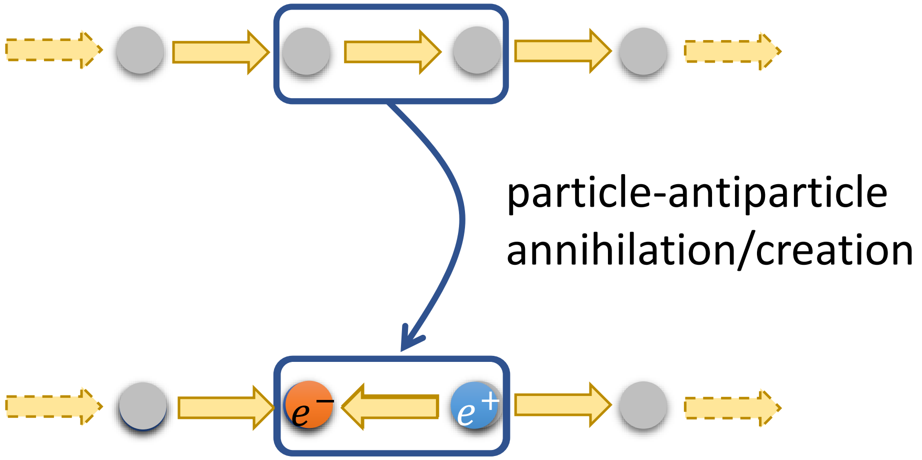
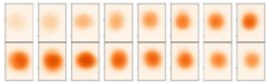
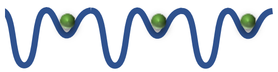




Key challenge:
How to teach a quantum device to obey local symmetry?

Realized in

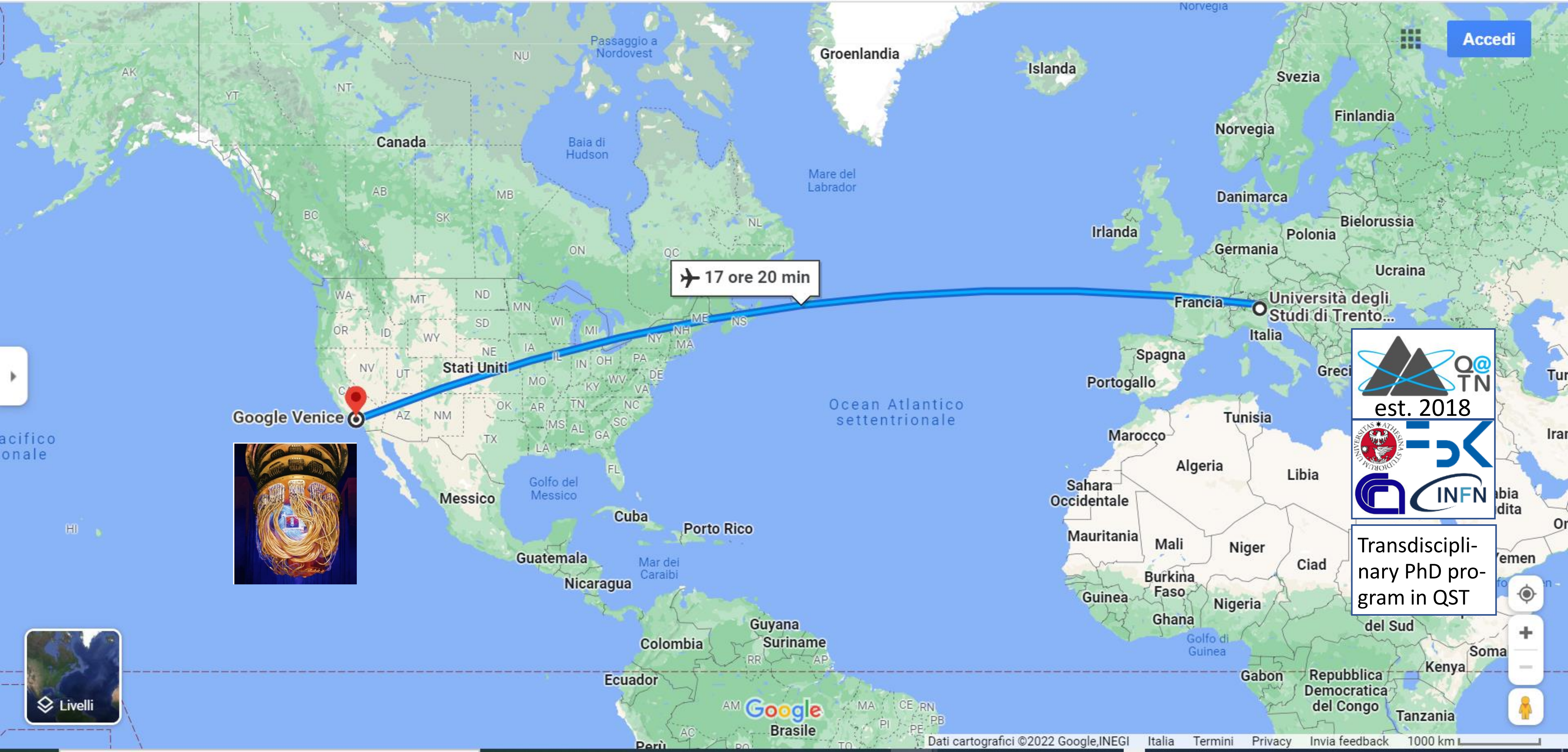
		# lattice sites
	**Trapped ions**	
	Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, *Nature* 2016	4
	Kokail, Maier, van Bijnen, Brydges, Joshi, Jurcevic, Muschik, Silvi, Blatt, Roos, Zoller, *Nature* 2019	20
	Rydberg atoms	
	Bernien, et al., *Nature* 2017	51
	Superconducting Qubits	
	Klco et al., *PRA* 2018	2
	**Neutral atoms**	
	Mil, Zache, Hegde, Xia, Bhatt, Oberthaler, Hauke, Berges, Jendrzejewski, *Science* 2020	2
	Yang, Sun, Ott, Wang, Zache, Halimeh, Yuan, Hauke, Pan, *Nature* 2020	35
	Zhou, Su, Halimeh, Ott, Sun, Hauke, Yang, Yuan, Berges, Pan, *arxiv* 2022	35

Next steps

- non-Abelian groups (see, e.g., talk Torsten Zache)
- Higher dimensions (see, e.g., Zohar *Phil. Trans. R. Soc. A* 2021)
- Discrete (Abelian) groups → this talk

Google Quantum AI Early Access Program

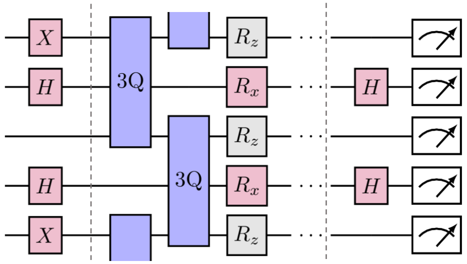
Exclusive cloud access to Google's quantum hardware (8 groups worldwide)



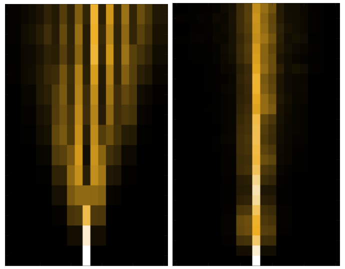
Transdisciplinary PhD program in QST

Our goals

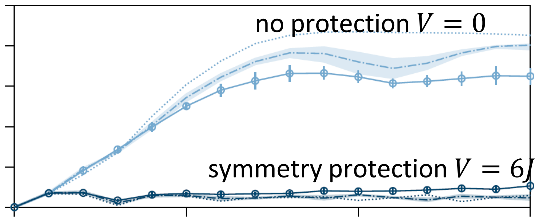
1. Design gauge-theory implementations

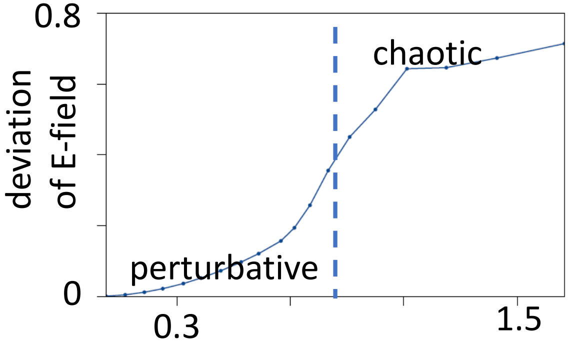


2. Do some interesting physics



3. Test error mitigation strategies

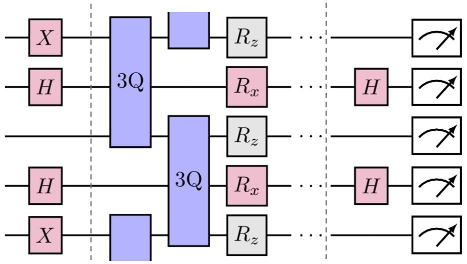




Mildenberger, Mruczkiewicz, Halimeh, Jiang, Hauke, arXiv:2203.08905

Outline

1. Design gauge-theory implementations



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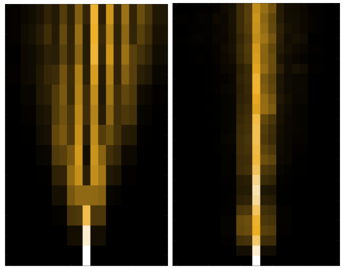

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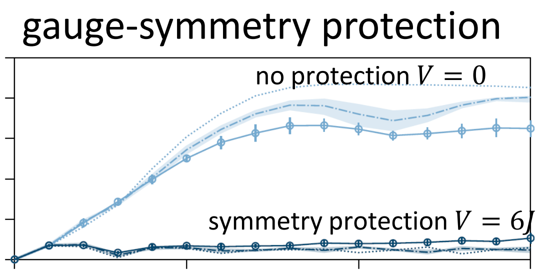
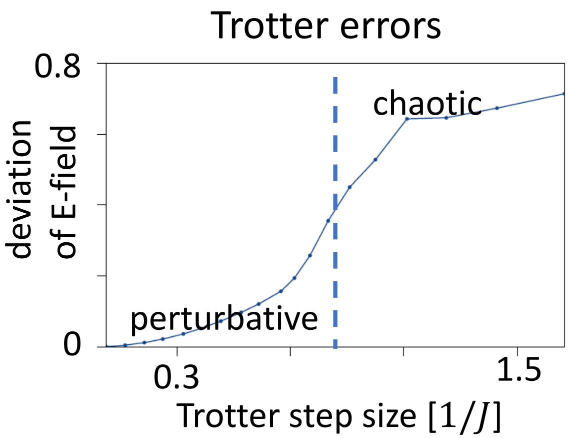




Mildenberger, Mruczkiewicz, Halimeh, Jiang, Hauke, arXiv:2203.08905

Target model: $\mathbb{Z}_2$ lattice gauge theory

$H = J\sum_i(\hat{\sigma}_i^+ \, \hat{\tau}^z_{i,i+1}\hat{\sigma}^-_{i+1} + \mathrm{h.c.}) + m\sum_i(-1)^i\hat{\sigma}_i^z - f\sum_i \tau^x_{i,i+1}$ $\quad G_i^{\mathbb{Z}_2} = -\tau^x_{i-1,i}\sigma_i^z\tau^x_{i,i+1}$

matter-gauge field coupling

rest mass

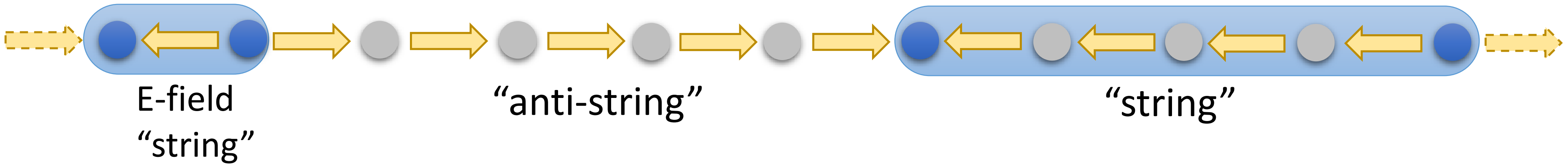
background field (in U(1): topological θ-angle)

Background field leads to confinement

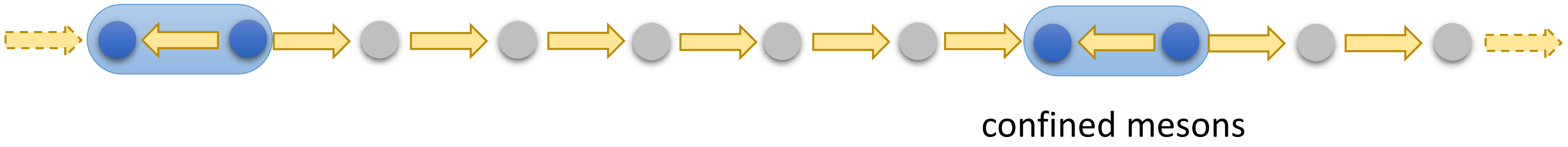
Kebrič, Barbiero, Reinmoser, Schollwöck, Grusdt, *PRL* 2021; Borla, Verresen, Grusdt, Moroz, *PRL* 2020

$$H = J \sum_i (\hat{\sigma}_i^+ \hat{\tau}_{i,i+1}^z \hat{\sigma}_{i+1}^- + \mathrm{h.c.}) + m \sum_i (-1)^i \hat{\sigma}_i^z - f \sum_i \tau_{i,i+1}^x \qquad G_i^{\mathbb{Z}_2} = -\tau_{i-1,i}^x \sigma_i^z \tau_{i,i+1}^x$$

at $f = 0$ E-field energy independent of L



at $f > 0$ E-field energy $\propto L$



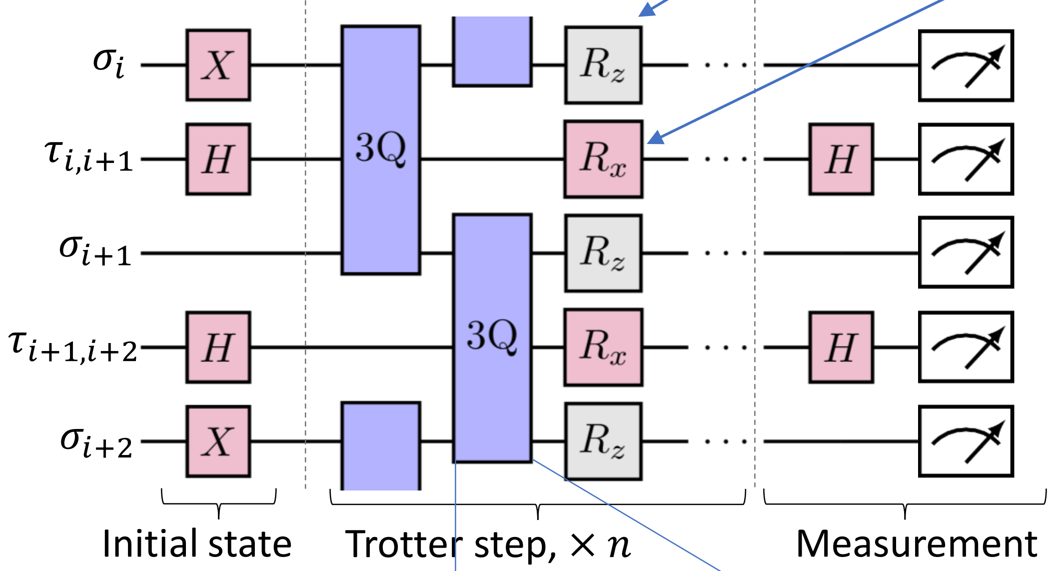
confinement in spin models, e.g.,
Kormos, Collura, Takács, Calabrese, *Nat. Phys.* 2017
Vovrosh, Knolle, *Scientific Reports* 2021
Lencsés, Mussardo, Takács, *Phys. Lett. B* 2022
Knaute, Hauke, Phys. Rev. A 2022

confinement in higher dimensional gauge theories, e.g.,
Lumia et al., arXiv:2112.11787
Huffman, Garcia Vera, Banerjee, arXiv:2109.15065
Mueller, Zache, Ott, arXiv:2107.11416
. . .

Our implementation scheme

$$H = J\sum_i(\hat{\sigma}_i^+\,\hat{\tau}^z_{i,i+1}\hat{\sigma}^-_{i,i+1} + \mathrm{h.c.}) + m\sum_i(-1)^i\hat{\sigma}_i^z - f\sum_i \tau^x_{i,i+1}$$

$$G_i^{\mathbb{Z}_2} = -\tau^x_{i-1,i}\sigma_i^z\tau^x_{i,i+1}$$



Challenge: implement this with native gate

$$\sqrt{iSWAP}^\dagger = e^{-\frac{i\pi}{4}(\sigma_1^+\sigma_2^- + h.c.)}$$

Perturbative scheme: Wang, Ge, Xiang, Song, Huang, Song, Guo, Su, Xu, Zheng, Fan, 2111.05048

Floquet approach single site: Schweizer et al., *Nat. Phys.* 2019 (see also Görg et al., *Nat. Phys.* 2019)

Our implementation scheme

$$H = J\sum_i(\hat{\sigma}_i^+\,\hat{\tau}^z_{i,i+1}\hat{\sigma}^-_{i,i+1} + \mathrm{h.c.}) + m\sum_i(-1)^i\hat{\sigma}_i^z - f\sum_i \tau^x_{i,i+1}$$

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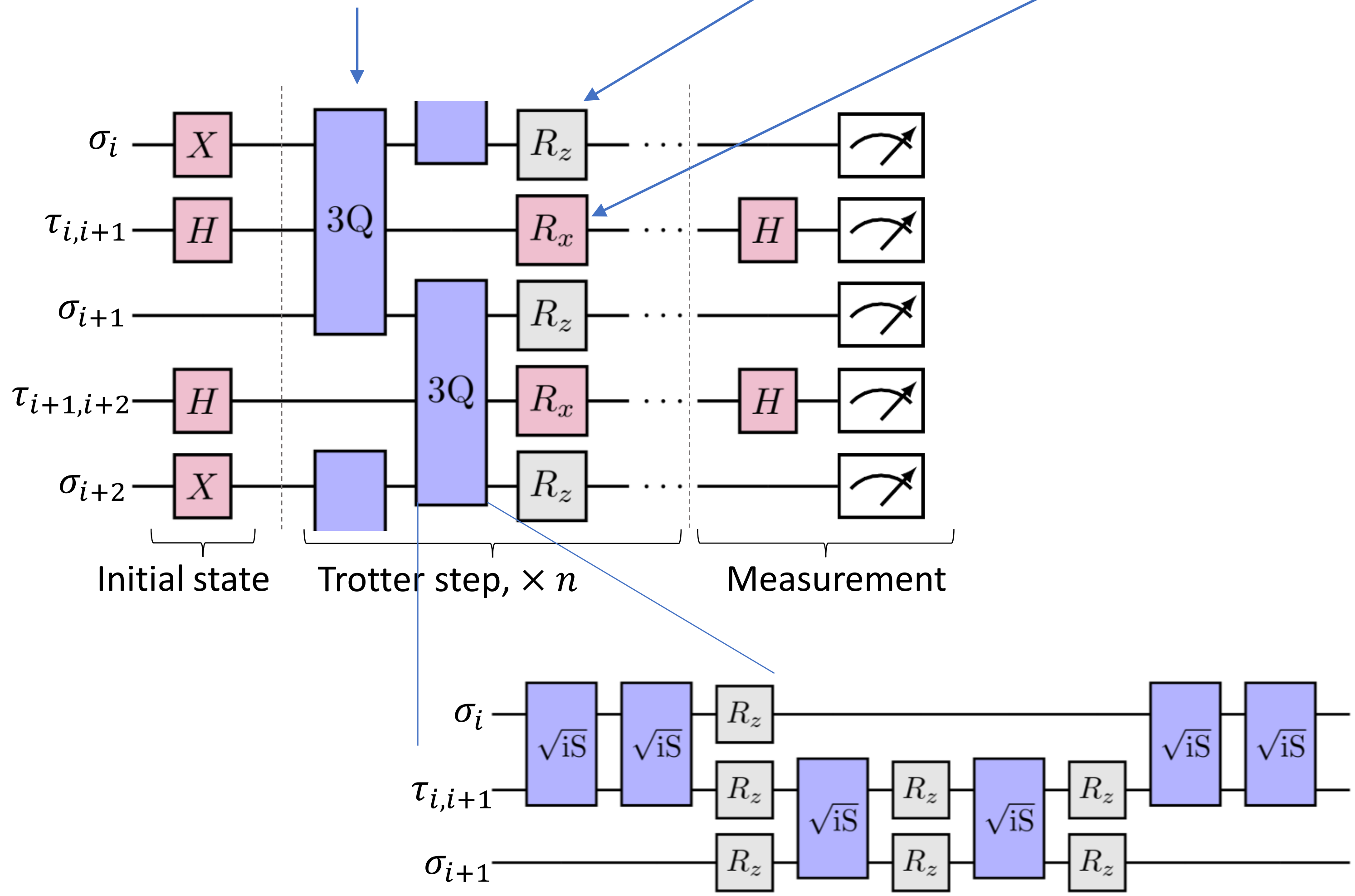
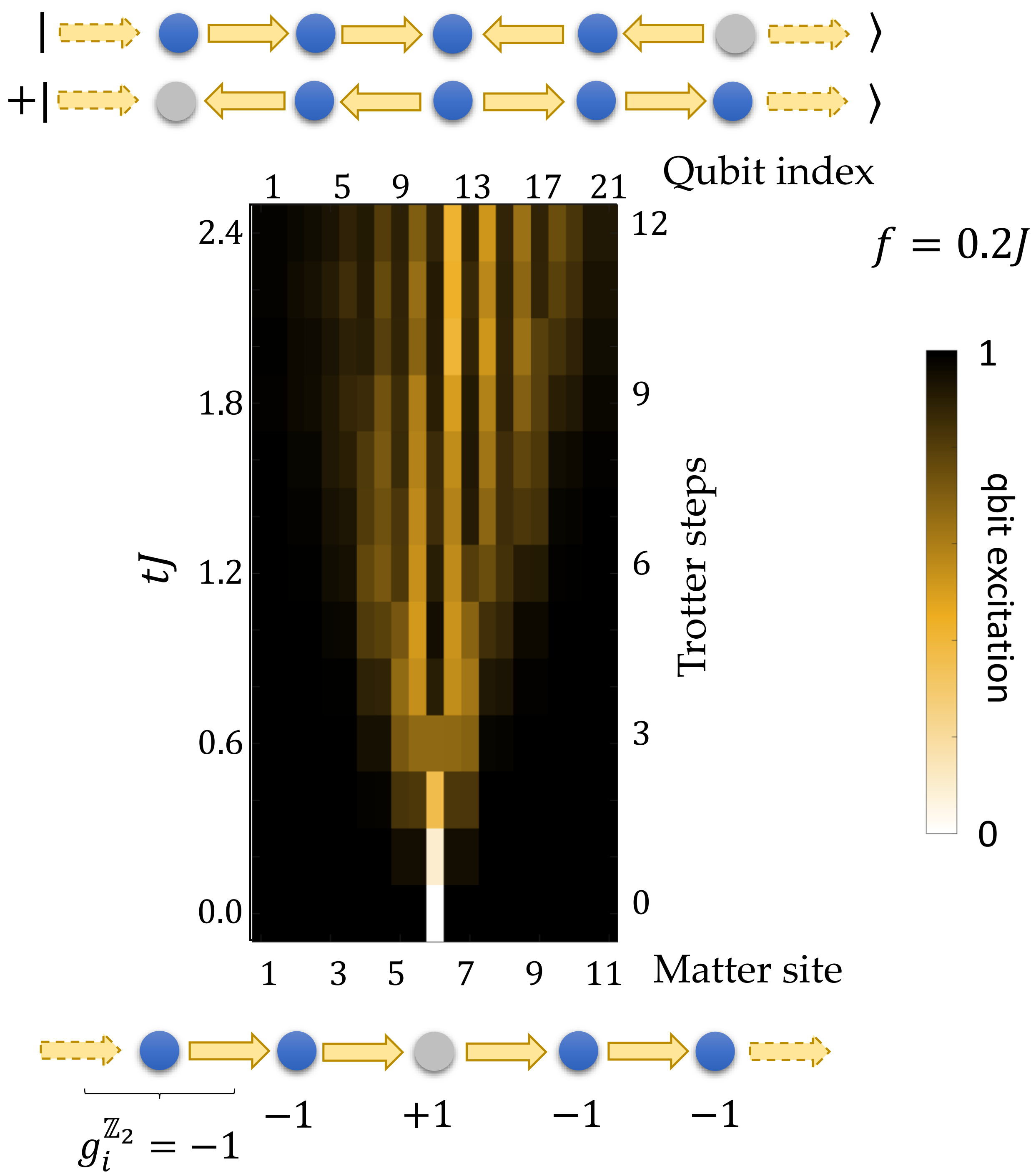
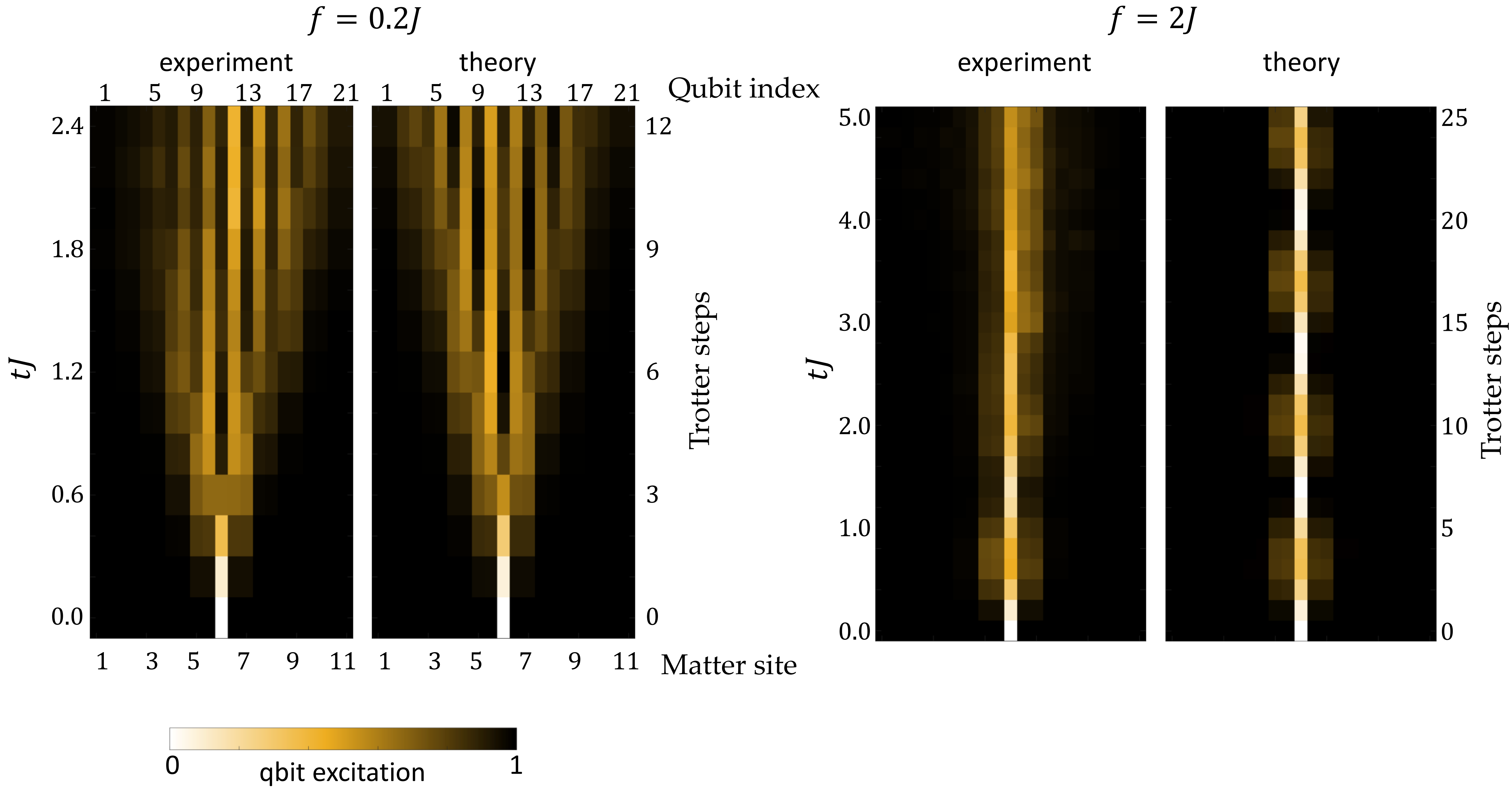




Qubit index
1 5 9 13 17 21
2.4
1.8
1.2
0.6
0.0
tJ
12
9
6
3
0
Trotter steps
1 3 5 7 9 11
Matter site
f = 0.2J
1
0
qbit excitation
g_i^{Z_2} = −1
−1
+1
−1
−1



$f = 0.2J$
$f = 2J$
experiment
theory
experiment
theory
Qubit index
1 5 9 13 17 21
Matter site
1 3 5 7 9 11
tJ
2.4 1.8 1.2 0.6 0.0
Trotter steps
12 9 6 3 0
5.0 4.0 3.0 2.0 1.0 0.0
25 20 15 10 5 0
0
qbit excitation
1

Excellent playground to test error mitigation strategies

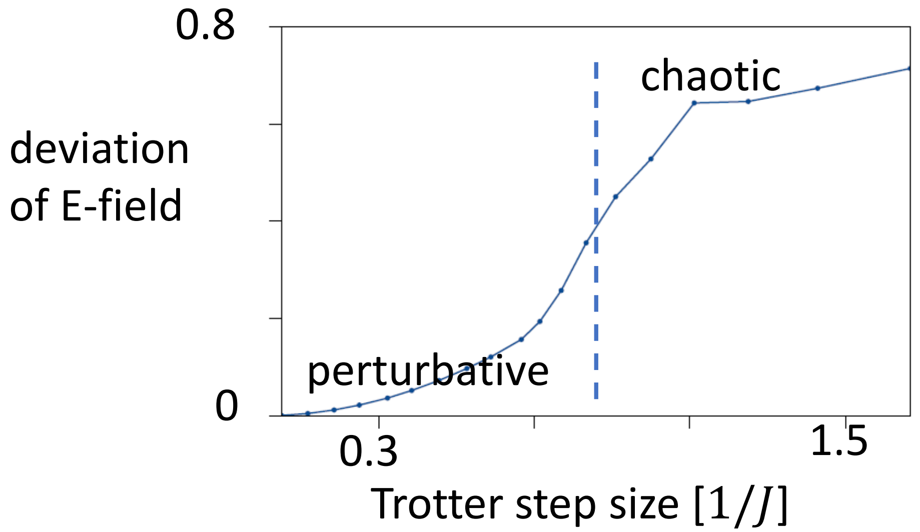
Trotter errors

Heyl, Hauke, Zoller, *Science Adv.* 2019

Sieberer, Olsacher, Elben, Heyl, Hauke, Haake, Zoller, npj QInf. 2019

Chinni, Munoz-Arias, Poggi, Deutsch, PRX Quantum 2022

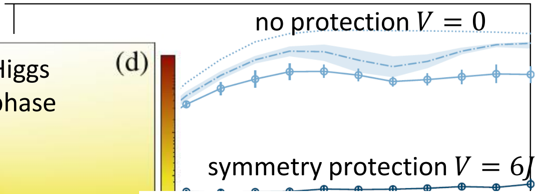
Kargi, Dehollain, Henriques, Sieberer, Olsacher, Hauke, Heyl, Zoller, Langford, arXiv:2110.11113



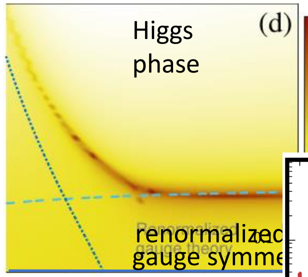
Mildenberger, Mruczkiewicz, Halimeh, Jiang, Hauke, 2203.08905

Excellent playground to test error mitigation strategies

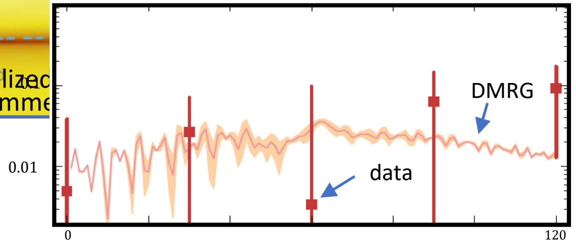
Gauge-symmetry protection



Mildenberger et al., arXiv:2203.08905



Van Damme, Halimeh, Hauke, arXiv:2010.07338



Yang, Sun, Ott, Wang, Zache, Halimeh, Yuan, Hauke, Pan, *Nature* 2020

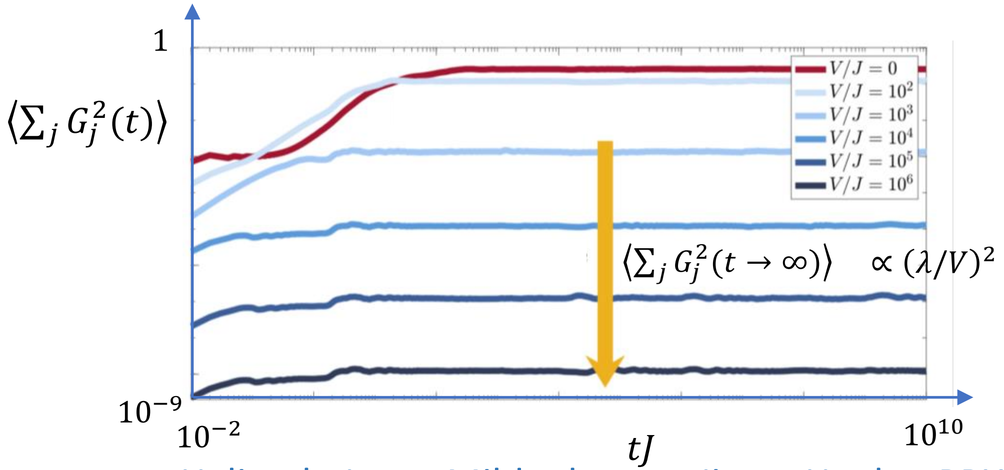
Realistic models always have violations of gauge symmetry

How to control these? suitable energy penalty

$H_{\text{real}} = H_0 + \lambda H_1 + V H_G$

$H_G = \sum_j c_j G_j$

$[H_0, G_j] = 0, [H_1, G_j] \neq 0$



Halimeh, Lang, Mildenberger, Jiang, Hauke, *PRX Quantum* 2021

Here

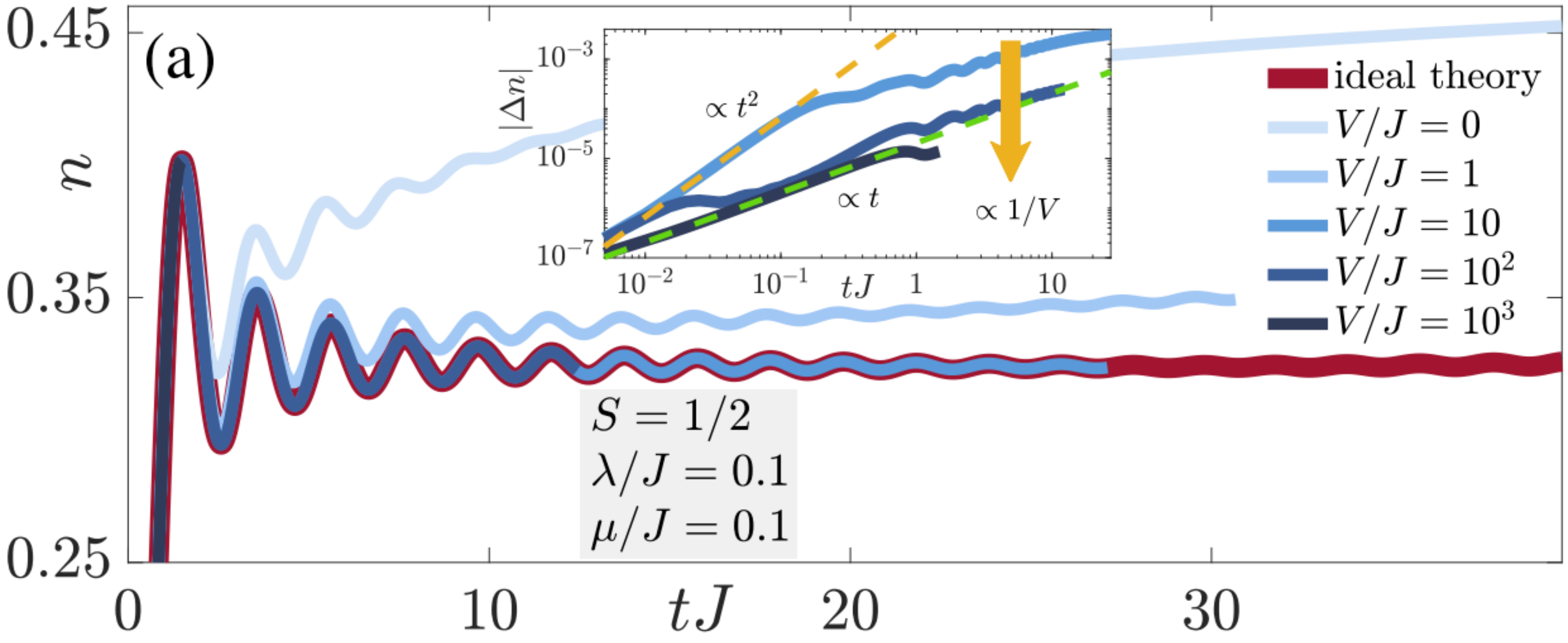
$H_0 = J \sum_i (\psi_i^\dagger \tau_{i,i+1}^+ \psi_{i+1} + \text{h.c.}) + m \sum_i (-1)^i \psi_i^\dagger \psi_i$

$H_1 = \lambda \sum_i \tau_{i,i+1}^x$

$G_i^{U(1)} = (\sigma_i^z + \tau_{i-1,i}^z - \tau_{i,i+1}^z + (-1)^i)/2$

See also Stannigel, Hauke, Marcos, Hafezi, Diehl, Dalmonte, Zoller, *PRL* 2014
Yang, Sun, Ott, Wang, Zache, Halimeh, Yuan, Hauke, Pan, *Nature* 2020
Lamm, Lawrence, Yamauchi, *Phys. Rev. D* 2019
Tran, Su, Carney, Taylor, *PRX Quantum* 2021
Kasper, Zache, Jendrzejewski, Lewenstein, Zohar, arXiv:2012.08620, …

Stability translates to other local observables



Van Damme, Lang, Hauke, Halimeh, arXiv:2104.07040

Coherent quantum Zeno effect

Facchi, Pascazio, *PRL* 2002

error $\leq tL^2\lambda^2/V$

Series of analytic bounds

Halimeh, Hauke, *PRL* 2020

Halimeh, Lang, Mildenberger, Jiang, Hauke, PRX Quantum

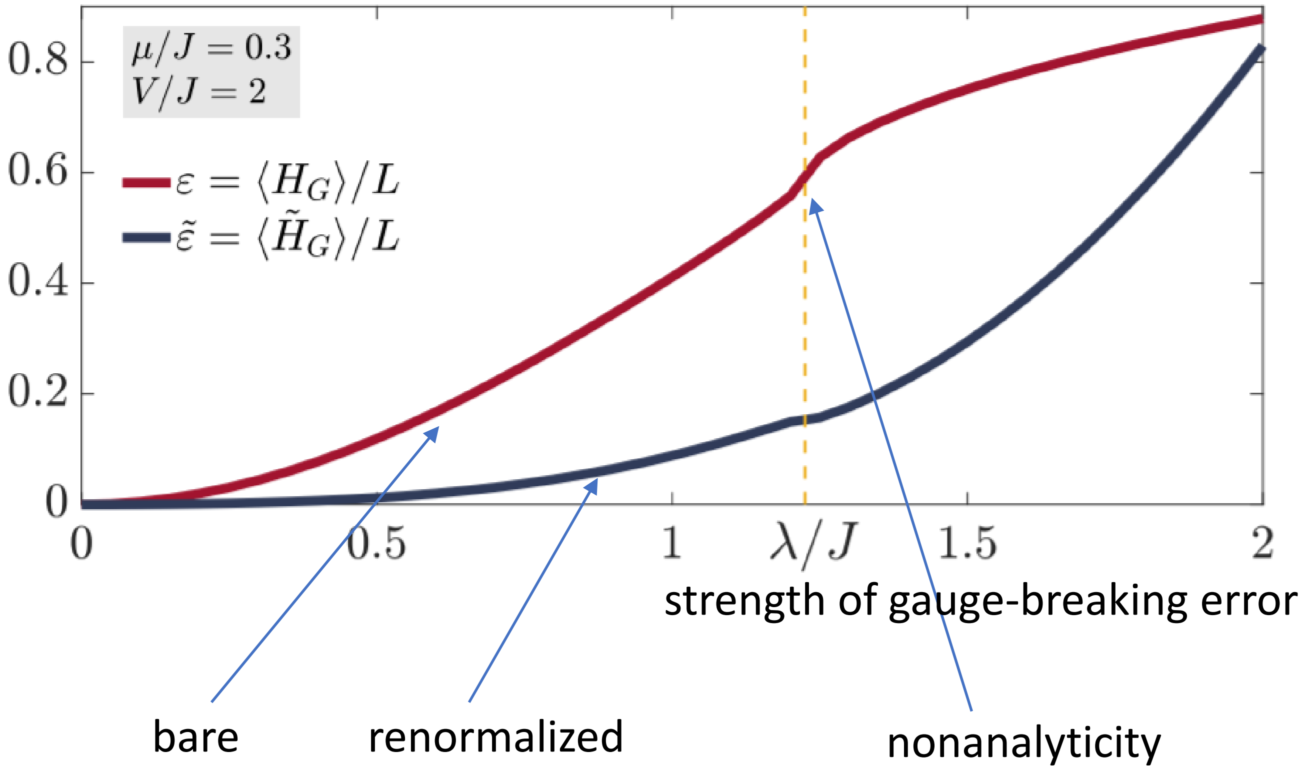
Van Damme, Lang, Hauke, Halimeh, arXiv:2104.07040

Ground-state transition

Van Damme, Hauke, Halimeh, arXiv:2010.07338

Emergence of a renormalized Gauss' law

violation of Gauss' law
$\langle H_G \rangle = \sum_j \langle G_j^2 \rangle$



Van Damme, Hauke, Halimeh, arXiv:2010.07338

We can use such protection also to tune the gauge symmetry

Add $U(1)$ gauge protection to $\mathbb{Z}_2$ LGT

$$H_{\mathbb{Z}_2} = J\sum_i(\hat{\sigma}_i^+ \hat{\tau}_{i,i+1}^z \hat{\sigma}_{i+1}^- + \mathrm{h.c.}) + m\sum_i(-1)^i\hat{\sigma}_i^z - f\sum_i \tau_{i,i+1}^x$$

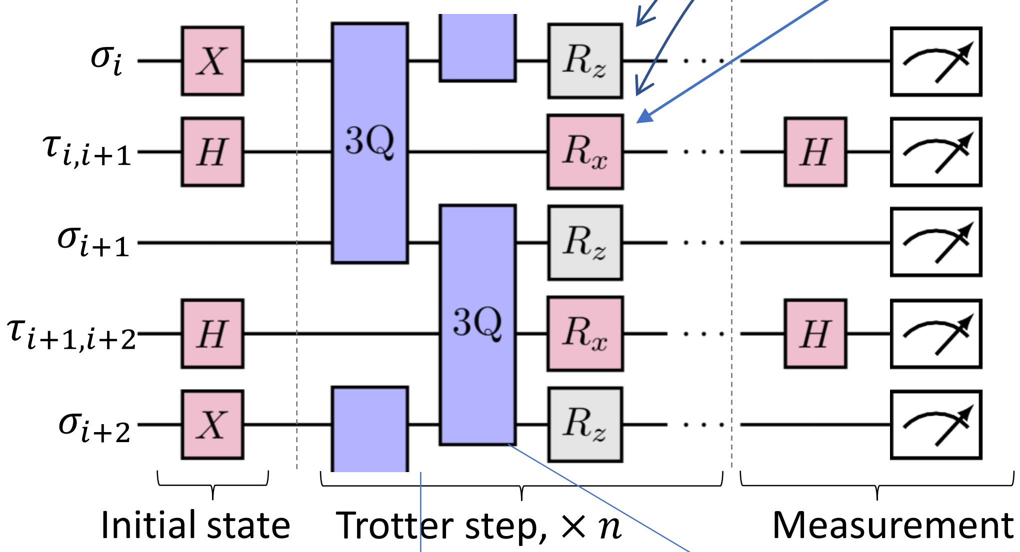
$$\left[H_{\mathbb{Z}_2}, G_i^{\mathbb{Z}_2}\right] = 0 \qquad G_i^{\mathbb{Z}_2} = -\tau_{i-1,i}^x \sigma_i^z \tau_{i,i+1}^x$$

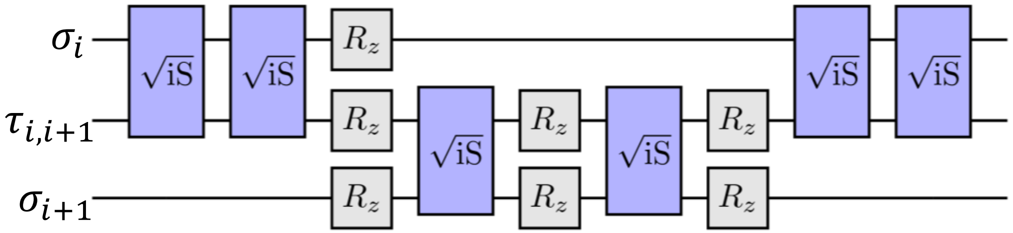
$$H = H_{\mathbb{Z}_2} + V H_G$$

$$\left[H_{\mathbb{Z}_2}, G_i^{U(1)}\right] \neq 0$$

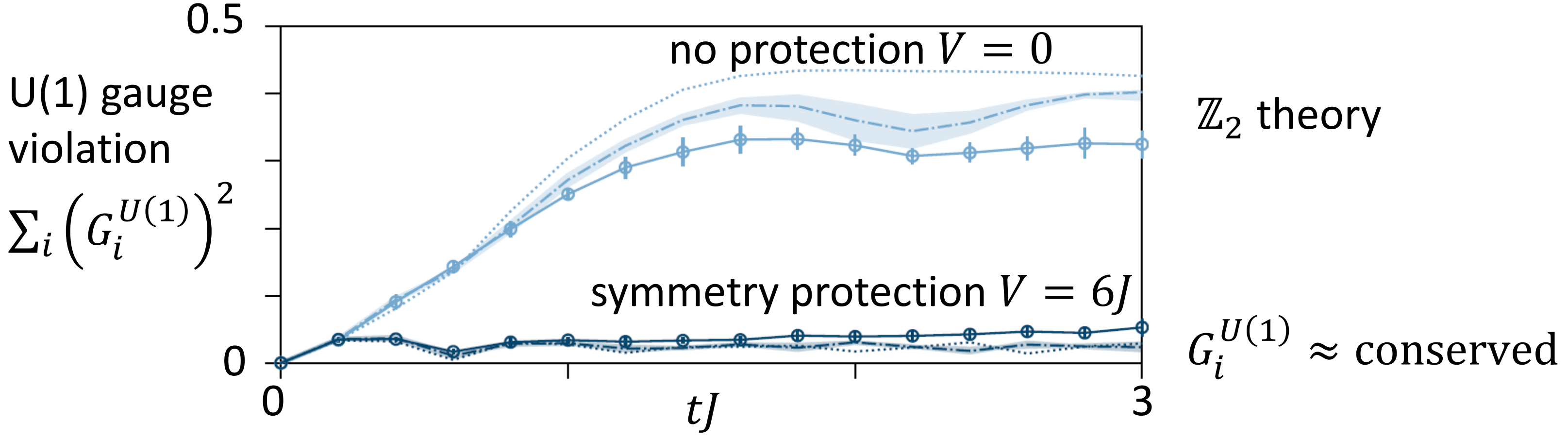
$$G_i^{U(1)} = (\sigma_i^z + \tau_{i-1,i}^x - \tau_{i,i+1}^x + (-1)^i)/2$$

$$H_G = \sum_i c_i\, G_i^{U(1)}$$

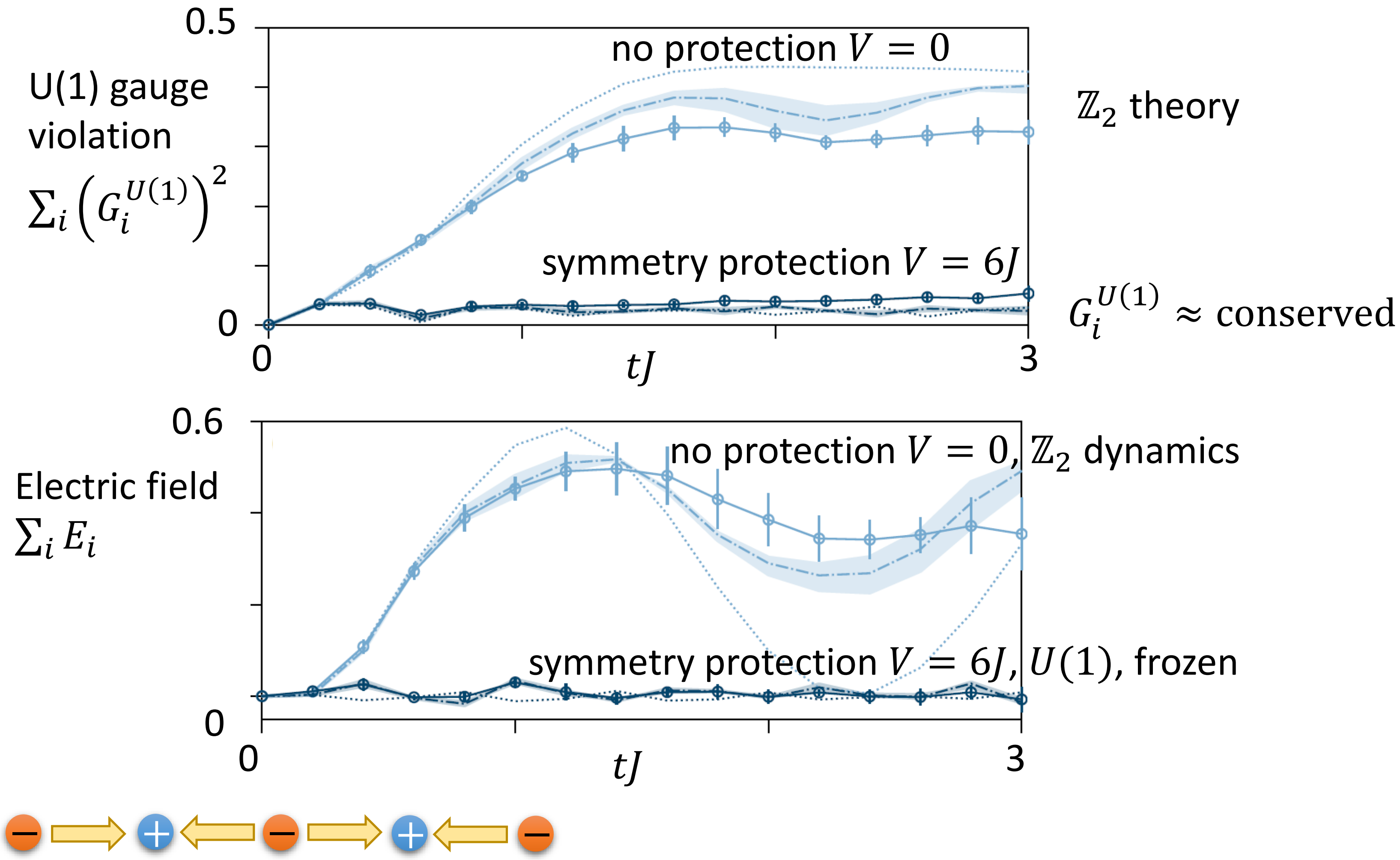




Gauge protection tunes symmetry



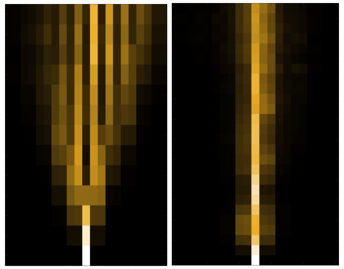
which can change drastically dynamics



Conclusions

Take away messages

- Quantum simulation of gauge theory is reaching system sizes to do some interesting physics



Dynamical topological transitions upon quench of θ–angle
Zache, Mueller, Schneider, Jendrzejewski, Berges, Hauke, *Phys. Rev. Lett.* 2019
Kharzeev, Kikuchi, *Phys. Rev. Research* 2020

Coleman phase transition
Yang, Sun, Ott, Wang, Zache, Halimeh, Yuan, Hauke, Pan, *Nature* 2020
Kokail, Maier, van Bijnen, Brydges, Joshi, Jurcevic, Muschik,
Silvi, Blatt, Roos, Zoller, *Nature* 2019
Bernien, et al., *Nature* 2017

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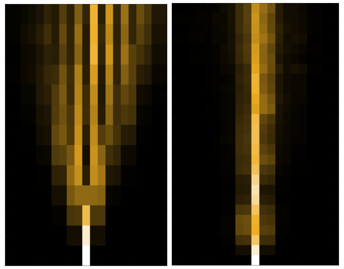
Take away messages

- Quantum simulation of gauge theory is reaching system sizes to do some interesting physics



- Energy penalties can controllably suppress gauge-symmetry violations

→ Deep questions about emergence of gauge invariance

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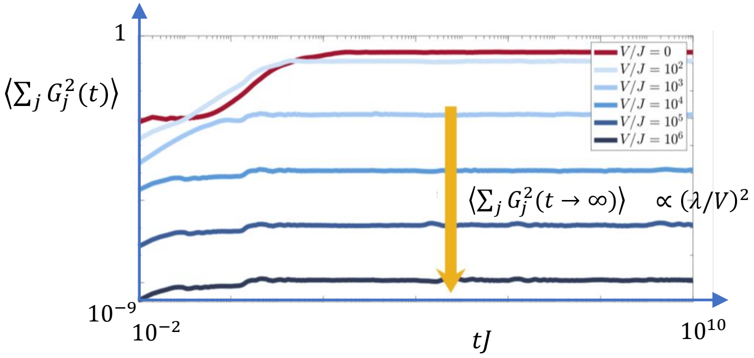

→ See talk Steven Bass

Thanks to Group Members & Collaborators

Quantum simulation





Soumik Bandyo-padhyay | Kevin Geier | **Haifeng Lang** | **Julius Mil-denberger** | Philipp Uhrich

Universal dynamics SYK model Bandyopad-hyay, Uhrich, Pavuglianiti, Hauke, 2108.01718

Analog cosmology in BEC Chatrchyan, Geier, Oberthaler, Berges, Hauke, *PRA* 2021

SOC & supersolidity Geier, Martone, Hauke, Stringari, *PRL* 2021

Collaborations: Many, e.g.,
Zoller & Blatt groups (Innsbruck),
Berges & Oberthaler groups (Heidelberg),
Zhang Jiang (Google), Jean-Philippe Brantut (EPFL),
Zhen-Sheng Yuan, Jian-Wei Pan (Hefei),
Marcello Dalmonte, Francesco Scazza (Trieste),
Bing Yang (SUNY), Quantera DYNAMITE (ICFO, …)

Quantum optimization


Veronica Panizza | Gopal Santra

Collaborations
www.enerquant.de
Sebastian Schmitt (Honda RI), Daniel Egger (IBM Zurich), Valentin Kasper, Maciej Lewenstein (ICFO), Davide Pastorello, Enrico Blanzieri, Pietro Faccioli (Trento)

Entanglement as resource


Sudipto Singha Roy | Ricardo Almeida

Multipartite entanglement of fermions
de Almeida, Hauke, *PRR* 2021

Collaborations
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Thank you!