Quantum simulation and non-equilibrium dynamics of the Sachdev-Ye-Kitaev model

Quantum Architectures for Analogues and Theory Applications, Trento

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Philipp Hauke

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INFN-TIFPA, Trento Institute for Fundamental Physics and Applications

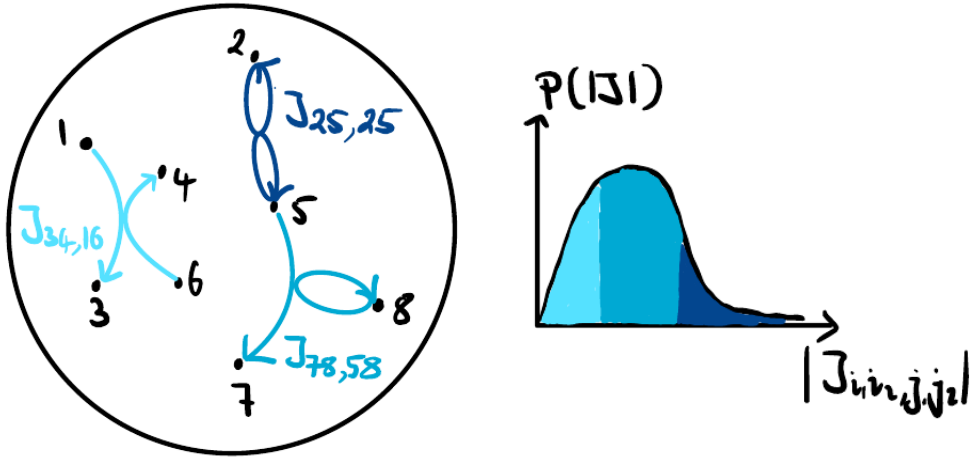
SERI project *Holograph*

Horizon Europe RIA *NeQST* (101080086)
Quantera II, Horizon 2020, *DYNAMITE* (101017733)
INFN specific initiative QUANTUM

Funded by the European Union

The SYK model —a new frontier for theory and experiment in quantum simulation

$$H^4_{\mathrm{SYK}} = \sum_{ijkl} J_{ijkl} c_i^\dagger c_j^\dagger c_k c_l \qquad \mathrm{var}(J_{ijkl}) \propto J^2$$

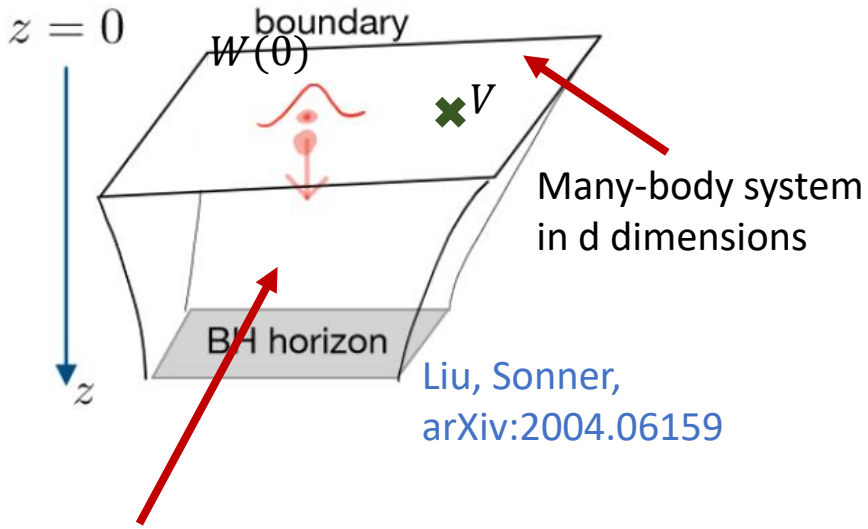


Kitaev KITP talks "*A simple model of quantum holography*" 2015
Sachdev, *PRX* **5** (2015)

Simplification of Sachdev-Ye model *Phys. Rev. Lett.*, 1993

A prototype for holographic quantum matter

Holographically dual to Jackiw-Teitelboim gravity

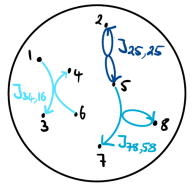


Liu, Sonner, arXiv:2004.06159

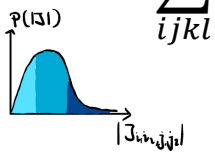
Gravity in d+1 dimensions

Artist's impression by Markus Gann/ Shutterstock

Sachdev-Ye-Kitaev model



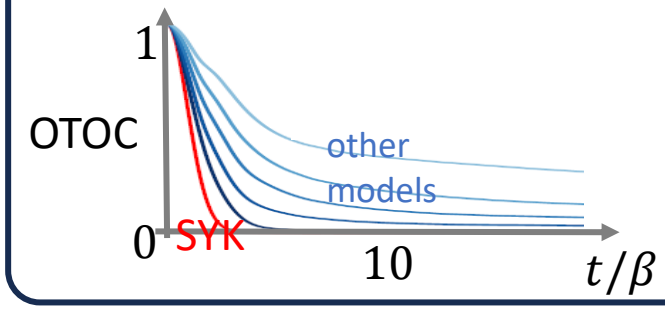
$$H^4_{\mathrm{SYK}} = \sum_{ijkl} J_{ijkl} c_i^\dagger c_j^\dagger c_k c_l$$



Maximal chaos/operator growth/scrambling

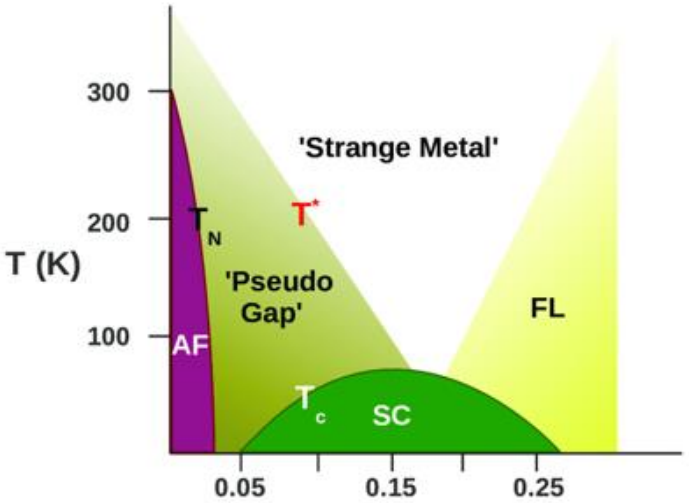
at $\beta J \gg 1$ (strong coupling) :
single scale $\kappa = 1/\beta$
saturates Lyapunov exp $\lambda = 2\pi/\beta$

$$\langle |[W(t), V(0)]|^2 \rangle_\beta \sim e^{\lambda t}$$



no quasiparticles,
emergent conformal symmetry

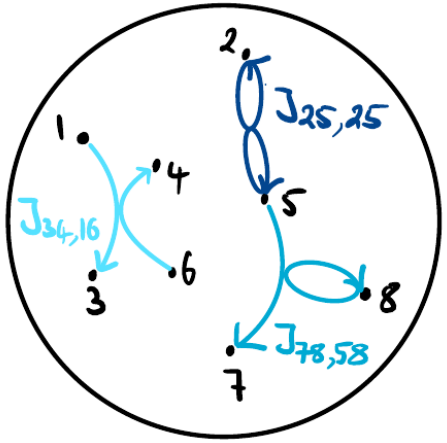
- **phenomen. model of strange metals**
- **proxy for quantum critical system**



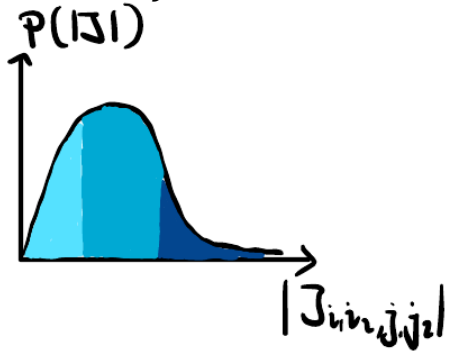
Picture: blog condensedconcepts

The main characteristic is also the main challenge:

How to obtain **infinite-ranged interactions** that are **random** and **uncorrelated** ?



$$H^4_{\mathrm{SYK}} = \sum_{ijkl} J_{ijkl} c_i^\dagger c_j^\dagger c_k c_l$$

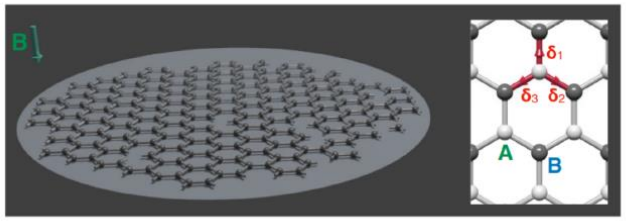


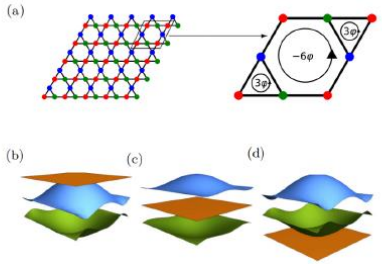
A series of proposals already exists

Analog devices

Graphene flakes, Majorana wires, optical lattices, molecules, . . .

Pikulin and Franz, PRX 2017; García-Álvarez *et al.*, PRL 2017; Danshita *et al.*, PTEP 2017; Chew *et al.*, PRB 2017; Chen, *et al.*, PRL 2018; Kuhlenkamp, Knap PRL 2020; . . .

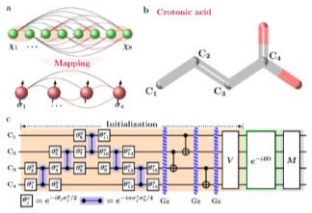




Not yet implemented

Quantum computers

Nuclear Magnetic Resonance, Superconducting qubits



Babbush *et al.*, PRA **99** (2019); Luo *et al.*, npj Q. Inf. **5** (2019); Bentsen *et al.*, PRL **123** (2019); Kim *et al.*, PRB **101** (2020); Wei and Sedrakyan, PRA **103** (2021);
Jafferis et al., Nature 612, **51** (2022); Kobrin et al., arXiv:2302.07897

Challenge: scalability ($N \leq 7$)

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Soumik Bandyopadyhay

Trento

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Jean-Philipp Brantut

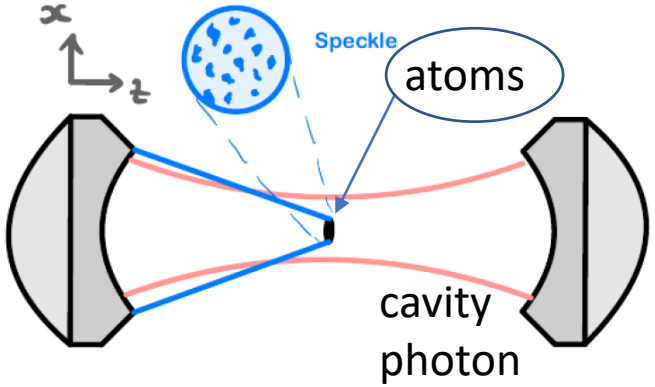
Lausanne

Julian Sonner

Geneva

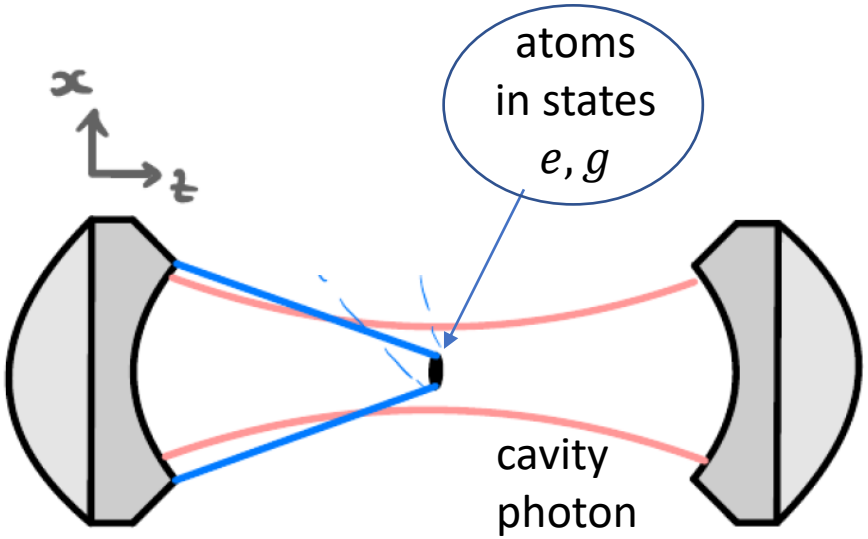
Cavity-QED quantum simulation of SYK model

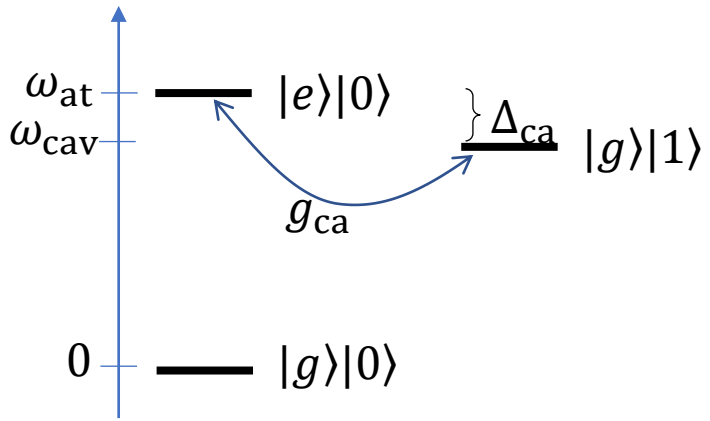
Uhrich, Bandyopadhyay, Sauerwein, Sonner, Brantut, Hauke
arXiv:2303.11343



$$H_{\text{eff}} = \sum_{ijkl} J_{ijkl} c_i^\dagger c_j^\dagger c_k c_l$$

Cold atoms in optical cavity – an ideal platform for long-ranged system



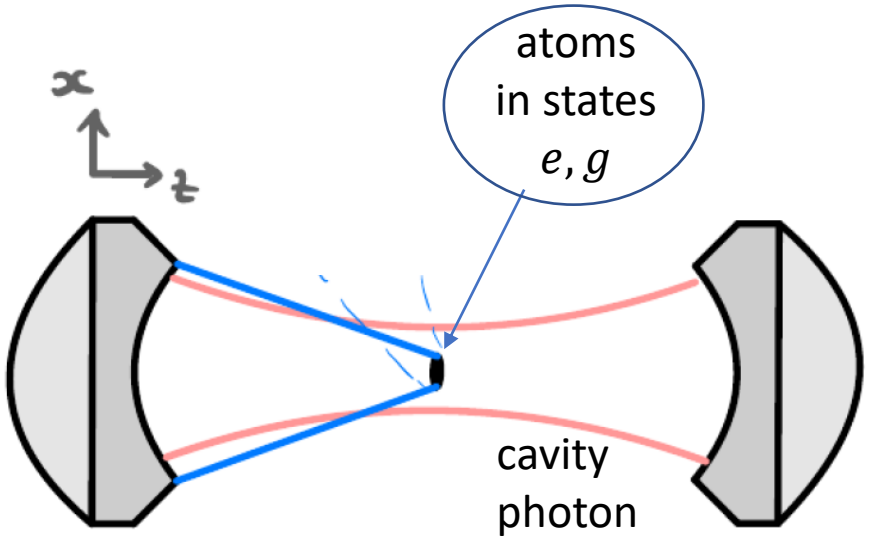


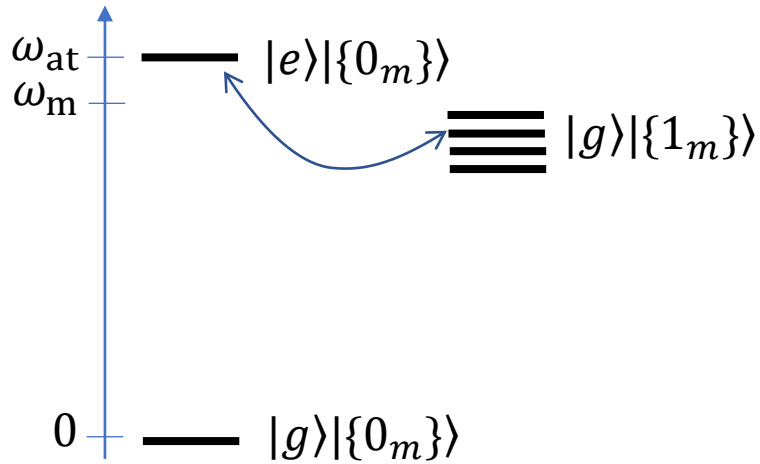
$$H = \int d\mathbf{r}\left(g_{\mathrm{ca}}(\boldsymbol{r})a\,\psi_e^{\dagger}(\mathbf{r})\psi_g\,(\mathbf{r}) + \mathrm{H.c.}\right) + \Delta_{\mathrm{ca}}a^{\dagger}\,a$$

talks to all atoms
but much structure,
not random

Experiments in many groups. In context of holographic quantum matter,
Periwal, Cooper, Kunkel, Wienand, Davis, and Schleier-Smith, *Nature* 600, 630 (2021)

We propose to use a multimode cavity



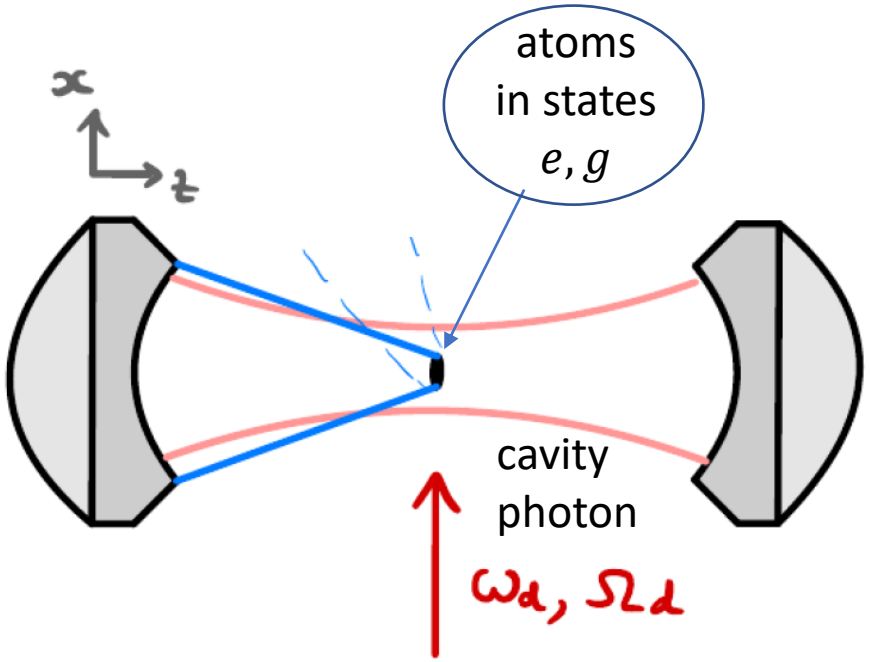


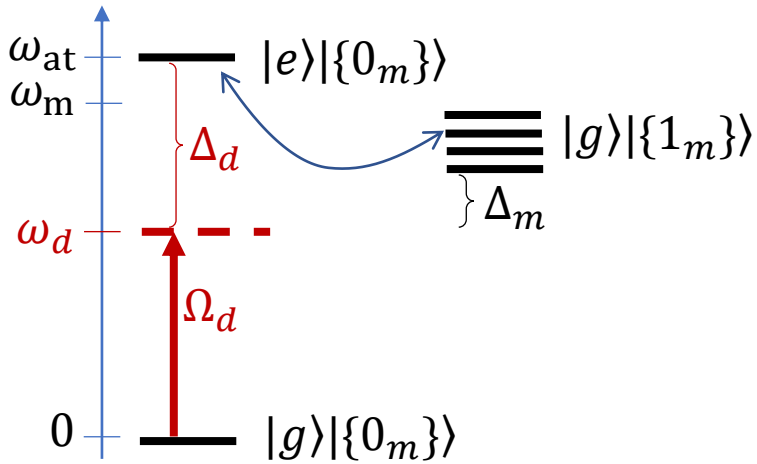
$$H = \sum_m \int d\mathbf{r} \left(g_m(\mathbf{r}) a_m \psi_e^\dagger(\mathbf{r}) \psi_g(\mathbf{r}) + \mathrm{H.c.} \right)$$

Multimode experiments, e.g., Lev group, *PRX* 2018

Related theory work in context of fermionic glasses, Müller, Strack, Sachdev *PRA* 2012

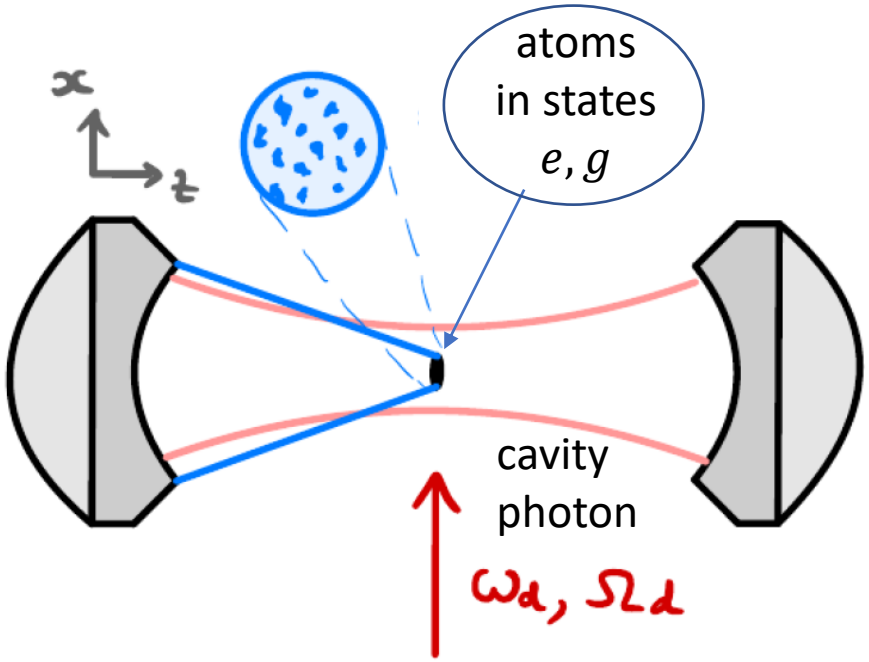
We propose to use a multimode cavity

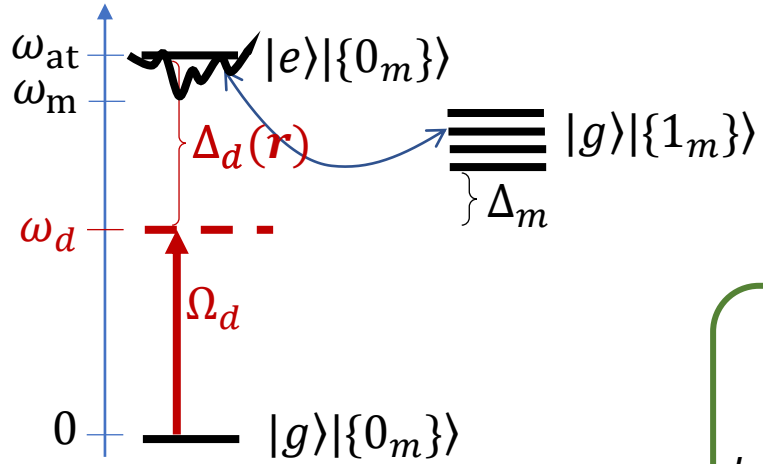




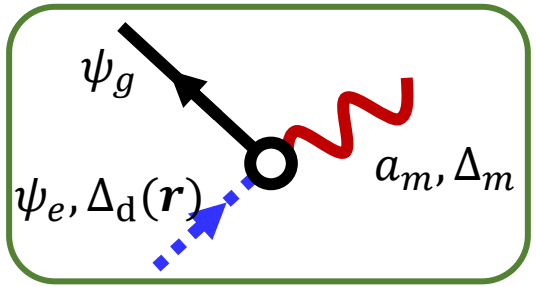
$$H = \sum_m \int d\mathbf{r}\left(g_m(\mathbf{r})a_m\,\psi_e^\dagger(\mathbf{r})\psi_g\,(\mathbf{r}) + \text{H. c.}\right) + \sum_m \Delta_m a_m^\dagger a_m$$
$$+\int d\mathbf{r}\left(\Omega_d\psi_e^\dagger(\mathbf{r})\psi_g\,(\mathbf{r}) + \text{H. c.}\right) + \int d\mathbf{r}\Delta_d(\mathbf{r})\psi_e^\dagger(\mathbf{r})\psi_e\,(\mathbf{r})$$

We propose to use a multimode cavity

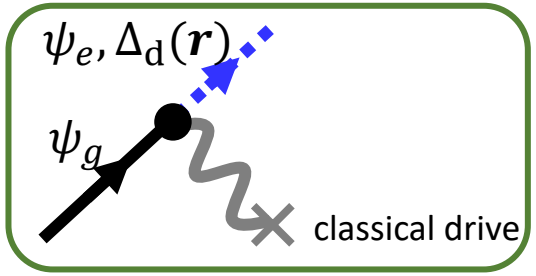




Can you not write all of that stuff in understandable language (= Feynman diagrams)?

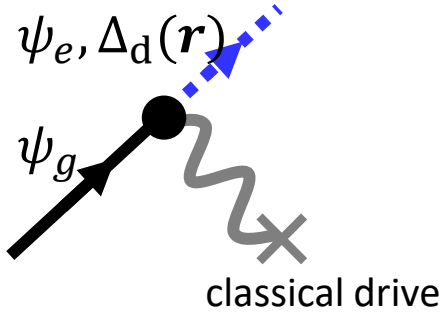


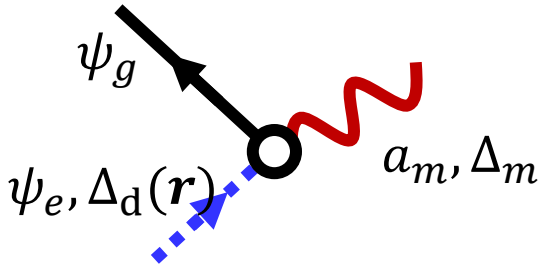
$$H = \sum_m \int d\mathbf{r} \left(g_m(\mathbf{r}) a_m \psi_e^\dagger(\mathbf{r}) \psi_g(\mathbf{r}) + \text{H.c.} \right) + \sum_m \Delta_m a_m^\dagger a_m$$
$$+ \int d\mathbf{r} \left(\Omega_d \psi_e^\dagger(\mathbf{r}) \psi_g(\mathbf{r}) + \text{H.c.} \right) + \int d\mathbf{r} \Delta_d(\mathbf{r}) \psi_e^\dagger(\mathbf{r}) \psi_e(\mathbf{r})$$



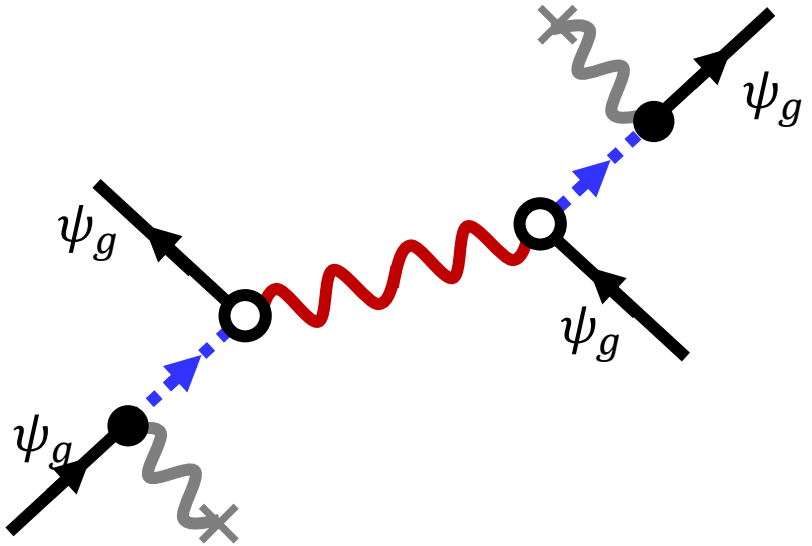
Summary of setup – in language of Feynman diagrams

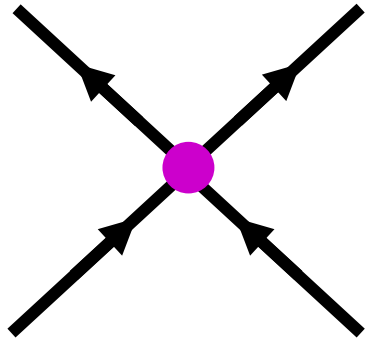
Elementary interactions





Resonant process

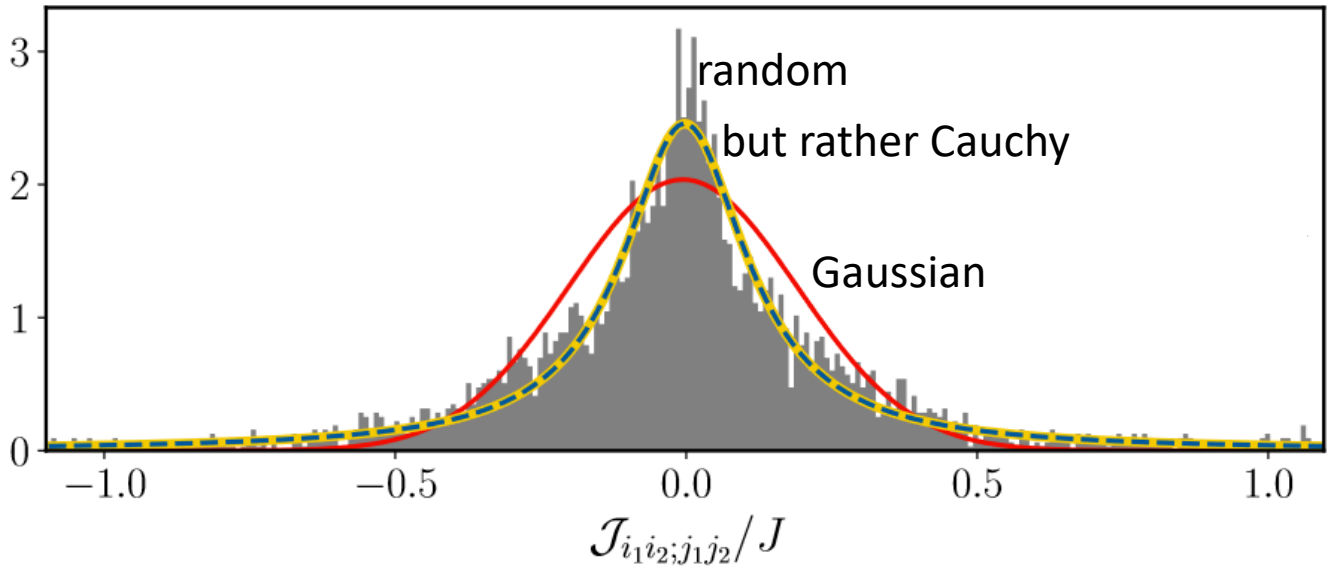




$$H_{\mathrm{eff}} = \sum_{ijkl} J_{ijkl} c_i^\dagger c_j^\dagger c_k c_l$$

Are the J_{ijkl} really random?

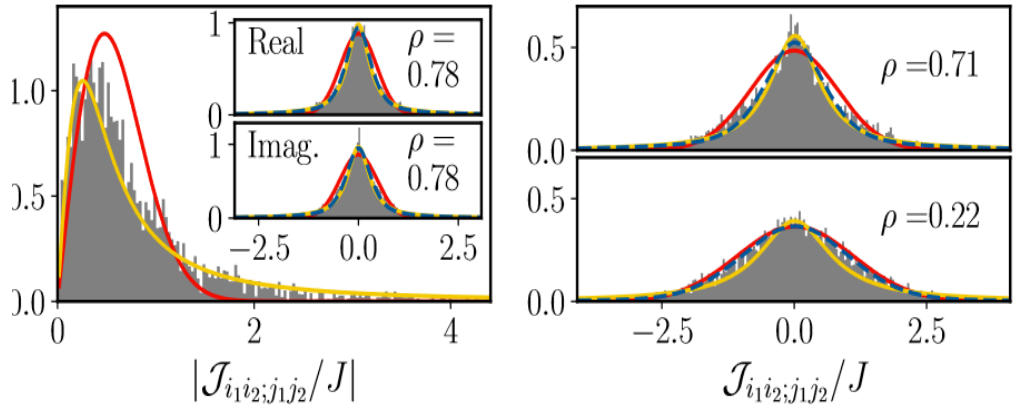
Numerics from “first principles” including speckle pattern etc.



We find, that happens also in

Chen, et al., *Phys. Rev. Lett.* 2018

Wei and Sedrakyan, *Phys. Rev. A* 2021



Interesting research question: what random distributions are “permissible”?

See, e.g., Krajewski, et al., *Phys. Rev. D* 2019; Cao, et al., *Science Bulletin* 2020; García-García, et al., *Phys. Rev. D* 2021; Tezuka, et al., *Phys. Rev. B* 2023

Legramandi, Bandyopadyhay, Uhrich, Hauke, in preparation

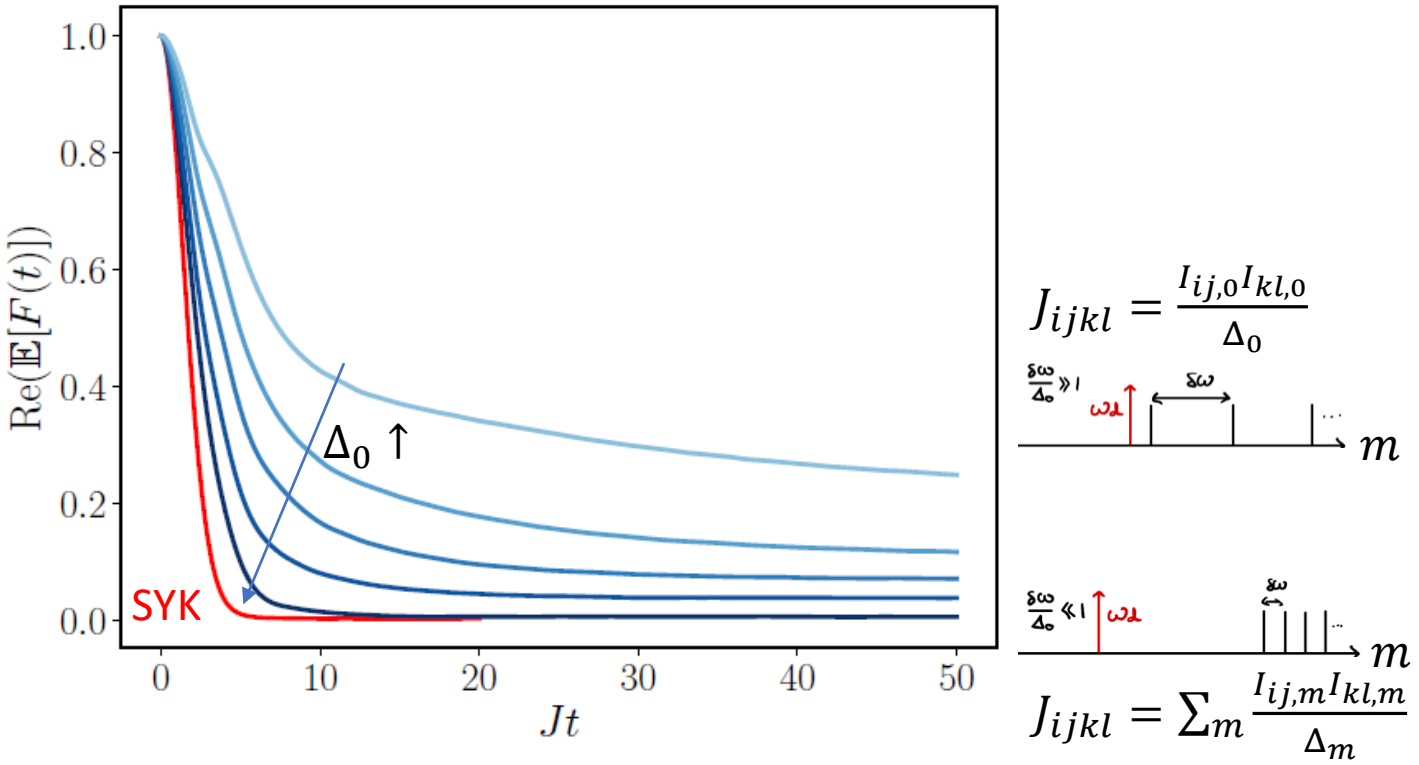
And what do such deformations mean on the gravity side?

Test physics, e.g., maximal short-time chaos

Fast scrambling as revealed by OTOC

$$F(t) = \mathrm{tr}\left(\rho_\beta W^\dagger(t) V^\dagger W(t) V\right)$$

$$W = 2c_1^\dagger c_1 - 1,\ V = 2c_2^\dagger c_2 - 1$$



Dynamics approaches that of SYK model!

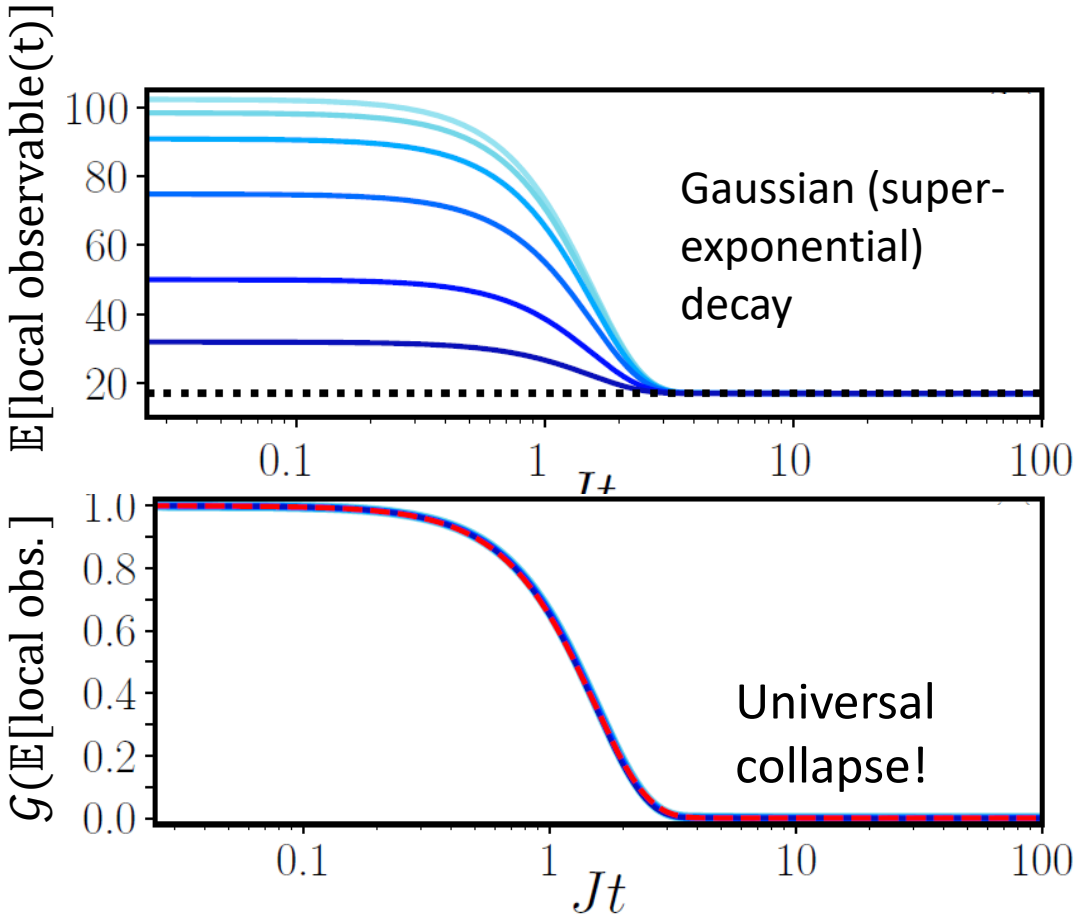
Note: relevant experimental time scales = few J !

Search for simpler observables reveals interesting physics

Abrupt quench at $t = 0$ into SYK Hamiltonian

simple rescaling

$$\mathcal{G}\left(f(t)\right) = \frac{f(t) - \overline{f(t)}}{f(0) - \overline{f(t)}}.$$



Potential experimental signature: occurs on very short time-scales!

S. Bandyopadyhay, P. Uhrich, A. Paviglianiti, P. Hauke, *QUANTUM* 2023

A. Paviglianiti, S. Bandyopadyhay, P. Uhrich, P. Hauke, *JHEP* 2022

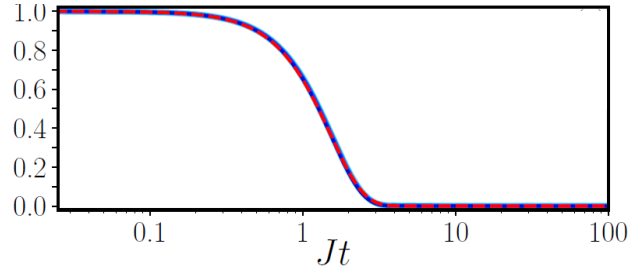
It is tough, but

There are lots of fascinating questions for theory and experiment along this road!

Unexpected universal dynamics as signature of maximal randomness

Bandyopadyhay, Uhrich, Paviglianiti, Hauke, *QUANTUM* 2023

Paviglianiti, Bandyopadyhay, Uhrich, Hauke, *JHEP* 2022

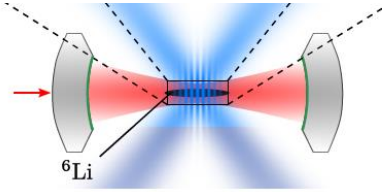


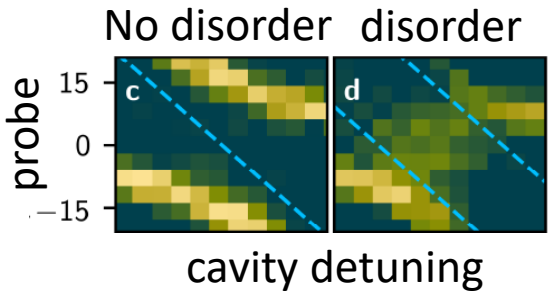
Eigenstate thermalization of non-Hermitian systems ($H \neq H^\dagger$)

Singha Roy, Bandyopadhyay, Costa de Almeida, Hauke, arXiv:2309.00049

"Simpler" setup leads to disordered systems

Sauerwein, Orsi, Uhrich, Bandyopadhyay, Mattiotti, Cantat-Moltrecht, Pupillo, Hauke, Brantut, *Nat. Phys.* 2023

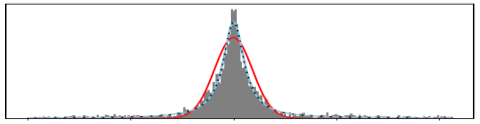




"grey states"

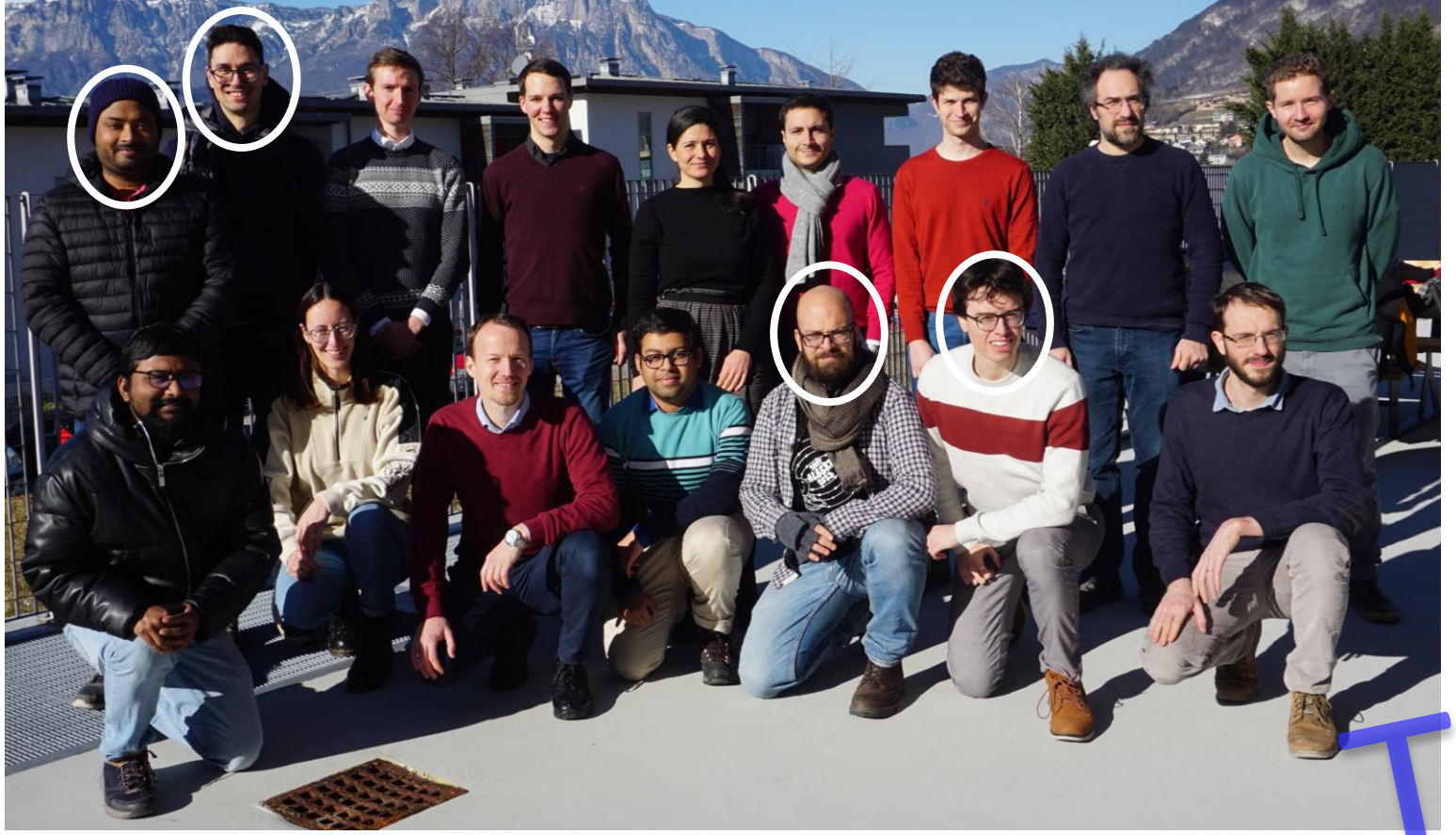
Large engineering challenge: try other models, other platforms. Neutral atoms, trapped ions, solid state

Experiments are not ideal, but show deformations of model



Does nature permit us to realize holographic matter?

What do deformations mean on gravity side?



Collaborators (on this project)

Trento: Philipp Uhrich, Soumik Bandyopadyhay, Andrea Legramandi, Alessio Paviglianiti, David Pascual, Alex Windey, Gianluca Rastelli, Iacopo Carusotto

Jean-Philipp Brantut (Lausanne),
Julian Sonner (Geneva),
Tilman Esslinger (Zürich),
Guido Pupillo (Strassburg)
and their groups

Thank you!

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ICSC – Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing, NextGenerationEU

SERI *Holograph*
BMBF MagicApp; Q@TN PhoQuaSDyn, HyClassQSampling
MUR FARE project DAVNE (R20PEX7Y3A)
Provincia Autonoma di Trento

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