Strange metals and black holes

Dirac Medal Award Ceremony
International Center for Theoretical Physics, Trieste
March 28, 2019

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

Thanks to students and postdocs, and many other collatorators

Students

- Jinwu Ye, Associate Professor, Department of Physics and Astronomy, Mississippi State University
  Thesis: Some Examples of Quantum Phase Transitions
- T. Senthil, Professor, Department of Physics, Massachusetts Institute of Technology.
  Thesis: Quantum Phase Transitions in Random Spin Systems
- Kedar Damle, Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai, India.
  Thesis: Turning on the Heat:Non-zero Temperature Dynamical Properties of Quantum Many-body Systems
- Chiranjeeb Buragohain, Microsoft Research.
  Thesis: Dynamical Properties of Quantum Antiferromagnets in One and Two Dimensions
- Ying Zhang, Finisterre Capital, London.
  Thesis: Competing Orders in the Cuprate Superconductors
- Anatoli Polkovnikov, Associate Professor, Boston University.
  Thesis: Manifestation of Quantum Fluctuations in Strongly Correlated Systems
- Stephen Powell, Assistant Professor, University of Nottingham
  Thesis: Quantum phases and transitions of many-body systems realized using cold atomic gases
- Adrian Del Maestro, Associate Professor, University of Vermont
  Thesis: The superconductor-metal quantum phase transition in ultra-narrow wires
- Emily Dunkel (with David Coker, Boston University), NASA Jet Propulsion Laboratory
  Thesis: Quantum Phenomena in Condensed Phase Systems
- Yang Qi, Institute for Advanced Studies, Tsinghua University
  Thesis: Spin and Charge Fluctuations in Strongly Correlated Systems.
- Rudro Rana Biswas, Assistant Professor, Purdue University
  Thesis: Explorations in Dirac Fermions and Spin Liquids.
- Eun Gook Moon, Assistant Professor, Korea Advanced Institute of Science and Technology
  Thesis: Superfluidity in Strongly Correlated Systems
- Max Metlitski, Assistant Professor, Department of Physics, Massachusetts Institute of Technology
  Thesis: Aspects of Critical Behavior of Two Dimensional Electron Systems
- Yejin Huh, Applied Scientist at Apple
  Thesis: Quantum Phase Transitions in d-wave Superconductors and Antiferromagnetic Kagome Lattices
- Susanne Pielawa, Lyft, Munich
  Thesis: Metastable Phases and Dynamics of Low-Dimensional Strongly-Correlated Atomic Quantum Gases
- Debanjan Chowdhury, Moore Foundation Postdoctoral Fellow, MIT
  Thesis: Interplay of Broken Symmetries and Quantum Criticality in Correlated Electronic Systems
- Junhyun Lee, Postdoctoral fellow, University of Maryland
  Thesis: Novel quantum phase transitions in low-dimensional systems
- Andrew Lucas, Postdoctoral fellow, Stanford University
  Thesis: Transport and hydrodynamics in holography, strange metals and graphene
- Shubhayu Chatterjee, Harvard University
- Aavishkar Patel, Harvard University
- Wenbo Fu, Harvard University
- Seth Whitsitt, Harvard University
- Alex Thomson, Harvard University
- Julia Steinberg, Harvard University

Thanks to students and postdocs, and many other collatorators

Postdocs

- Pierre Le Doussal, Directeur de Recherche de Classe Exceptionnelle, Laboratoire de Physique Théorique de l' Ecole Normale Supérieure, Paris, France.
- Rodolfo Jalabert, Professeur à l'Université Louis Pasteur, Institut de Physique et Chimie des Matériaux de Strasbourg, France.
- Andrey Chubukov, William I. and Bianca M. Fine Chair in Theoretical Physics, University of Minnesota, Minneapolis.
- Satya Majumdar, Directeur de Recherche, Laboratoire de Physique Théorique et Modèles Statistiques, University of Paris XI, France.
- Matthias Vojta, Chair of Theoretical Solid State Physics, Technische Universität, Dresden, Germany
- Oleg Starykh, Professor, Department of Physics, University of Utah.
- Marcus Kollar, Theoretische Physik III, Institut für Physik, Universität Augsburg, Germany.
- Kwon Park, Professor, Korea Institute for Advanced Study, Seoul.
- Takao Morinari, Kyoto University, Kyoto, Japan.
- Adam Durst, Associate Professor, Hofstra University.
- Krishnendu Sengupta, Professor, Indian Association for the Cultivation of Science, Kolkata, India.
- Lorenz Bartosch, Assistant Professor, University of Frankfurt.
- Predrag Nikolic, Associate Professor, George Mason University
- Ribhu Kaul, Associate Professor, University of Kentucky
- Markus Müller, Scientist, Paul Scherrer Institute, Switzerland.
- Lars Fritz, Assistant Professor, University of Utrecht
- Michael Levin, Associate Professor, University of Chicago
- Cenke Xu, Associate Professor, University of California, Santa Barbara
- Sean Hartnoll, Associate Professor, Stanford University
- Erez Berg, Associate Professor, University of Chicago
- Liang Fu, Lawrence C. (1944) and Sarah W. Biedenharn Career Development Associate Professor of Physics, Massachusetts Institute of Technology
- Liza Huijse, Software Engineer at Karius, Inc.
- Chris Laumann, Assistant Professor, Boston University
- Matthias Punk, Faculty, LMU Munich
- Philipp Strack, ZEISS Group
- Brian Swingle, Assistant Professor, University of Maryland
- Dmitry Abanin, Professor of Physics, University of Geneva
- Ling-Yan (Janet) Hung, Professor of Physics, Fudan University, Shanghai
- Jay Sau, Assistant Professor, University of Maryland
- Sarang Gopalakrishnan, Postdoctoral Fellow, Caltech
- Andrea Allais, Cruise Automation, San Francisco
- Johannes Bauer, SCL Group, London
- Paul Chesler, Harvard University
- Andreas Eberlein, Harvard University
- William Witczak-Krempa, Assistant Professor, University of Montreal
- Richard Davison, Harvard University
- Chong Wang, Harvard University
- Mathias Scheurer, Harvard University.

Ordinary metals:
quasiparticles

Strange metals:
no quasiparticles

Black
holes

Ordinary metals:
quasiparticles

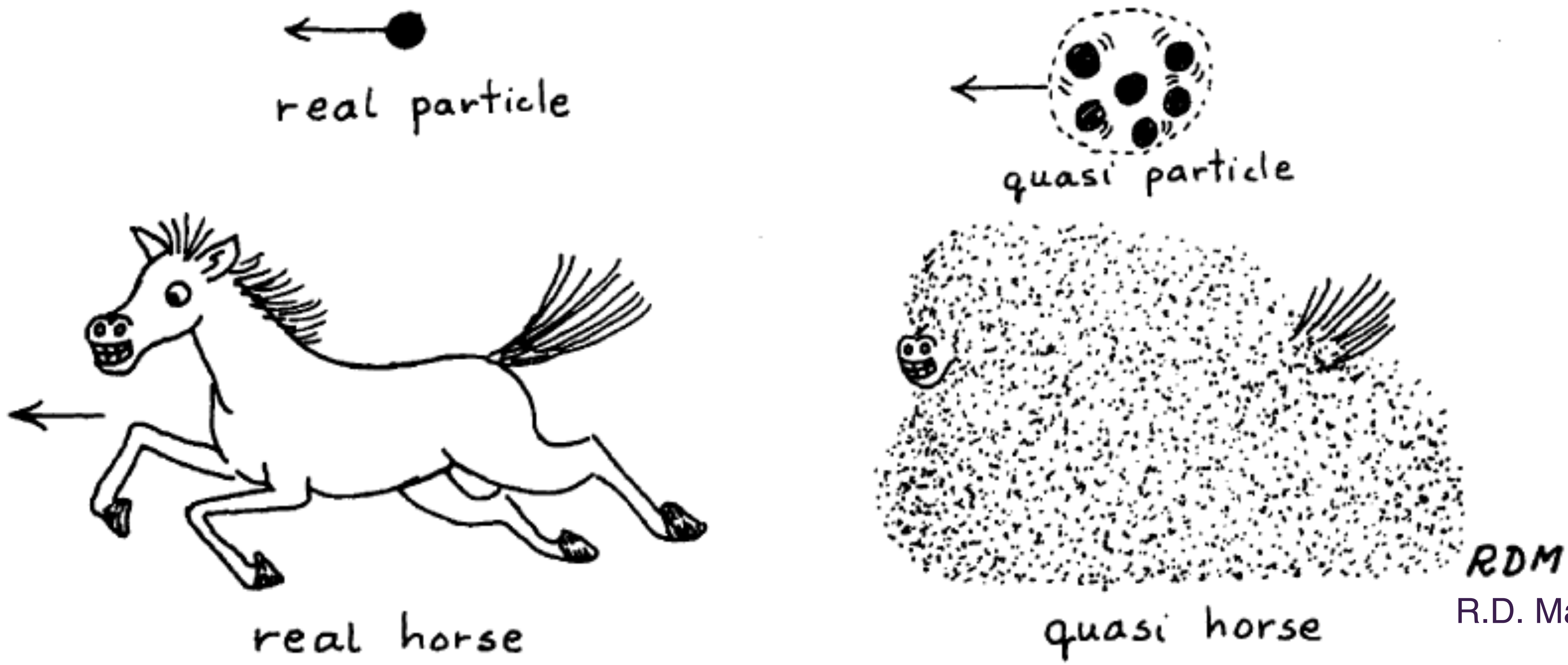
Strange metals:
no quasiparticles

Black holes

Ordinary metals

Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal

Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an "excited lump" in the many-electron state which responds just like an ordinary particle.



R.D. Mattuck

What are quasiparticles ?

- **Quasiparticles are additive excitations:**
  The low-lying excitations of the many-body system can be identified as a set $\{n_\alpha\}$ of quasiparticles with energy ε_α

$$E = \sum_\alpha n_\alpha \varepsilon_\alpha + \sum_{\alpha,\beta} F_{\alpha\beta} n_\alpha n_\beta + \ldots$$

In a lattice system of N sites, this parameterizes the energy of $\sim e^{\alpha N}$ states in terms of poly(N) numbers.

What are quasiparticles ?

- Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time diverges as

$$\tau_{\text{eq}} \sim \frac{\hbar U^2 / E_F}{(k_B T)^2} \quad , \quad \text{as } T \to 0,$$

  where U is the strength of interactions and E_F is the Fermi energy.

What are quasiparticles ?

- Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time diverges as

$$\tau_{\text{eq}} \sim \frac{\hbar U^2/E_F}{(k_B T)^2} \quad , \quad \text{as } T \to 0,$$

  where U is the strength of interactions and E_F is the Fermi energy.

- This time is much longer than the 'Planckian time' $\hbar/(k_B T)$, which we will find in systems without quasiparticle excitations.

$$\tau_{\text{eq}} \gg \frac{\hbar}{k_B T} \quad , \quad \text{as } T \to 0.$$

Ordinary metals:
quasiparticles

Strange metals:
no quasiparticles

Black
holes

Remarkable recent observation of 'Planckian' strange metal transport in cuprates, pnictides, magic-angle graphene, and ultracold atoms: the resistivity is associated with a universal scattering time $\approx \hbar/(k_B T)$.

Universal *T*-linear resistivity and Planckian dissipation in overdoped cuprates

NATURE PHYSICS | VOL 15 | FEBRUARY 2019 | 142–147

A. Legros[1,2], S. Benhabib[3], W. Tabis[3,4], F. Laliberté[1], M. Dion[1], M. Lizaire[1], B. Vignolle[3], D. Vignolles[3], H. Raffy[5], Z. Z. Li[5], P. Auban-Senzier[5], N. Doiron-Leyraud[1], P. Fournier[1,6], D. Colson[2], L. Taillefer[1,6*] and C. Proust[3,6*]

arXiv:1902.01034

Planckian dissipation and scale invariance in a quantum-critical disordered pnictide

Yasuyuki Nakajima,[1,2] Tristin Metz,[2] Christopher Eckberg,[2] Kevin Kirshenbaum,[2] Alex Hughes,[2] Renxiong Wang,[2] Limin Wang,[2] Shanta R. Saha,[2] I-Lin Liu,[2,3,4] Nicholas P. Butch,[2,4] Zhonghao Liu,[5,6] Sergey V. Borisenko,[5] Peter Y. Zavalij,[7] and Johnpierre Paglione[2,8]

Strange metal in magic-angle graphene with near Planckian dissipation

Yuan Cao,[1,*] Debanjan Chowdhury,[1,*] Daniel Rodan-Legrain,[1] Oriol Rubies-Bigordà,[1] Kenji Watanabe,[2] Takashi Taniguchi,[2] T. Senthil,[1,†] and Pablo Jarillo-Herrero[1,†]

arXiv:1901.03710

Bad metallic transport in a cold atom Fermi-Hubbard system

Science **363**, 379–382 (2019)

Peter T. Brown[1], Debayan Mitra[1], Elmer Guardado-Sanchez[1], Reza Nourafkan[2], Alexis Reymbaut[2], Charles-David Hébert[2], Simon Bergeron[2], A.-M. S. Tremblay[2,3], Jure Kokalj[4,5], David A. Huse[1], Peter Schauß[1*], Waseem S. Bakr[1]†

Remarkable recent observation of 'Planckian' strange metal transport in cuprates, pnictides, magic-angle graphene, and ultracold atoms: the resistivity, ρ, is

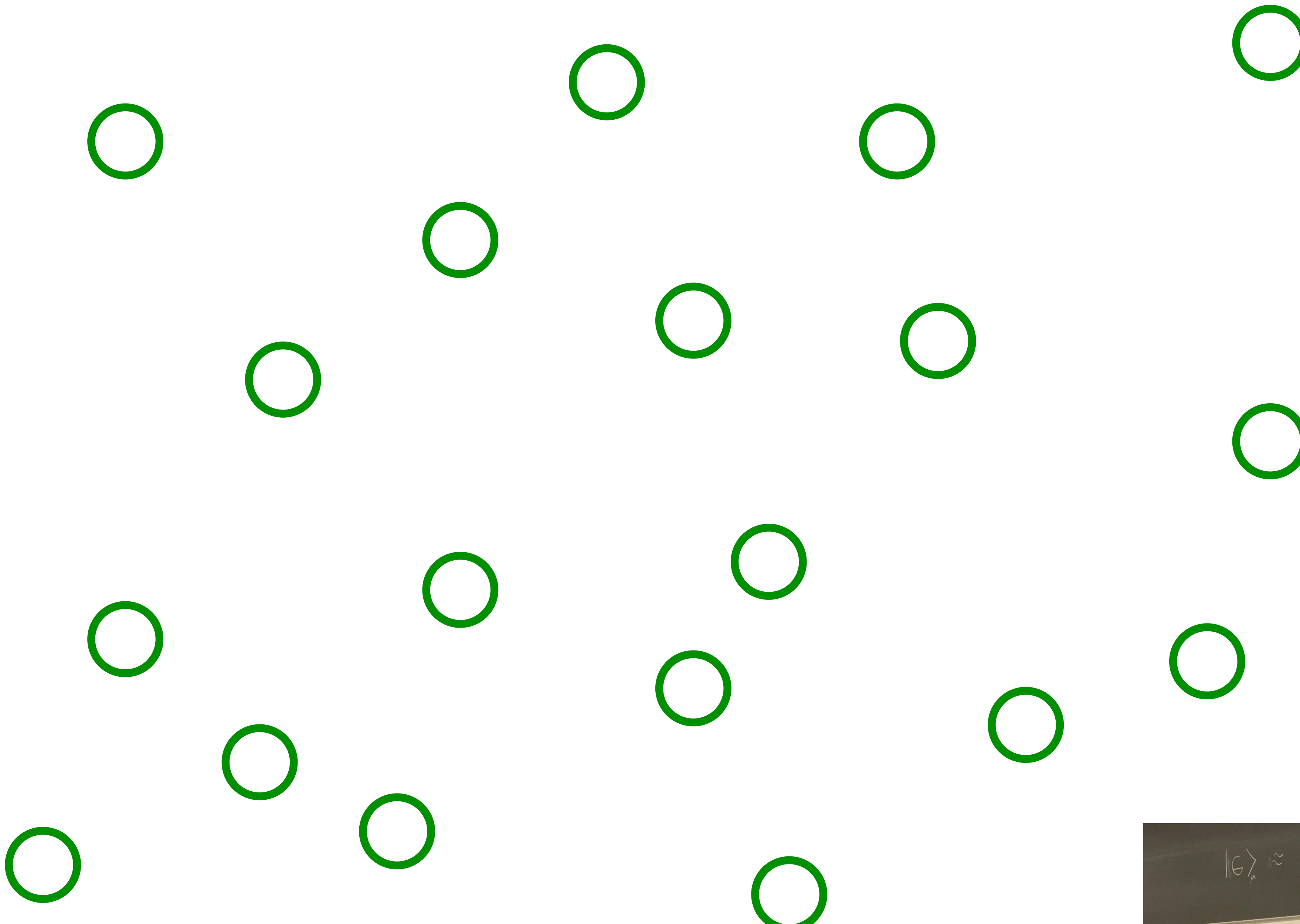
$$\rho = \frac{m^*}{ne^2}\frac{1}{\tau}$$

with a universal scattering rate

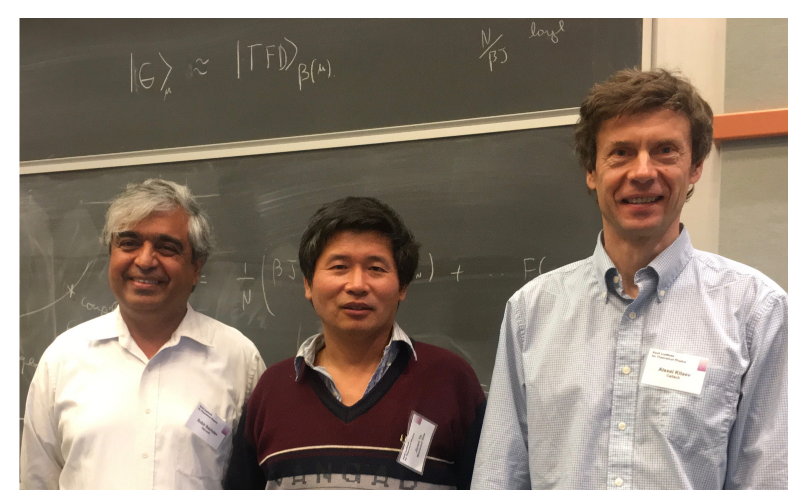
$$\frac{1}{\tau} \approx \frac{k_B T}{\hbar},$$

independent of the strength of interactions!

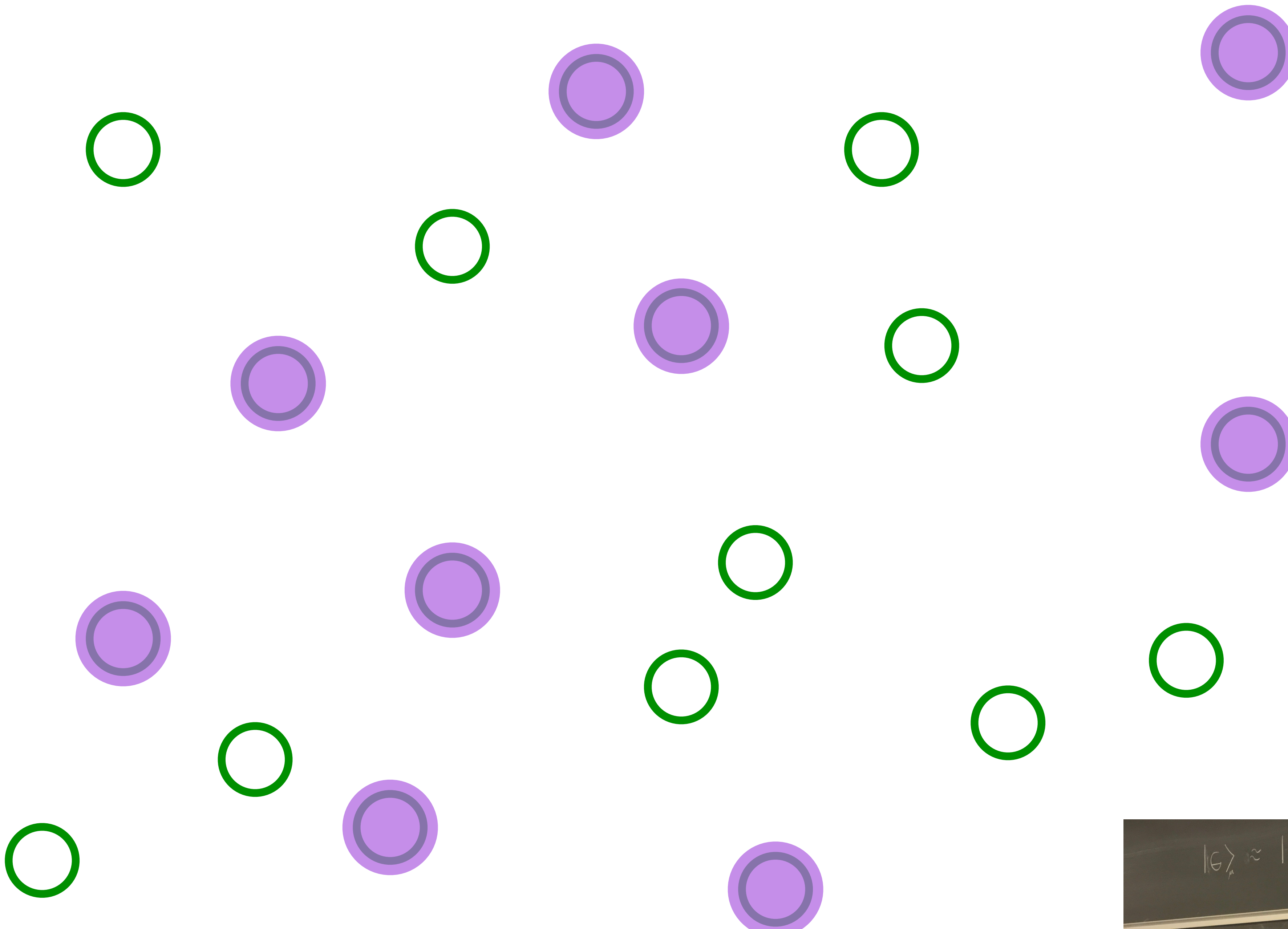
The Sachdev-Ye-Kitaev (SYK) model

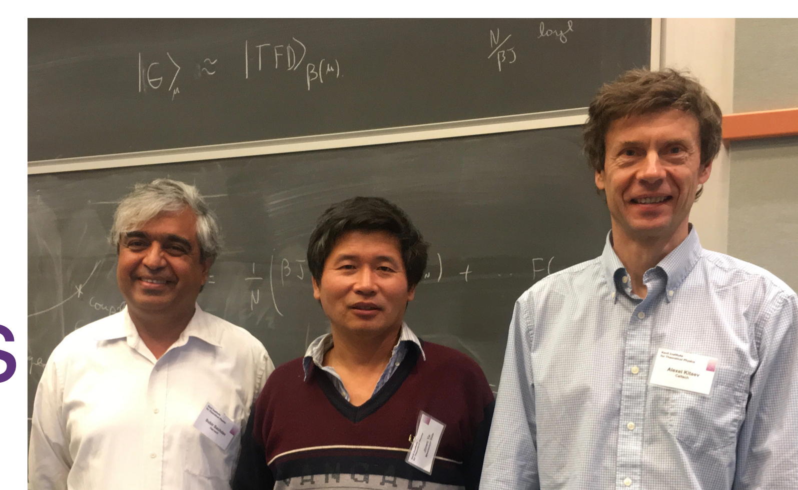


Pick a set of random positions



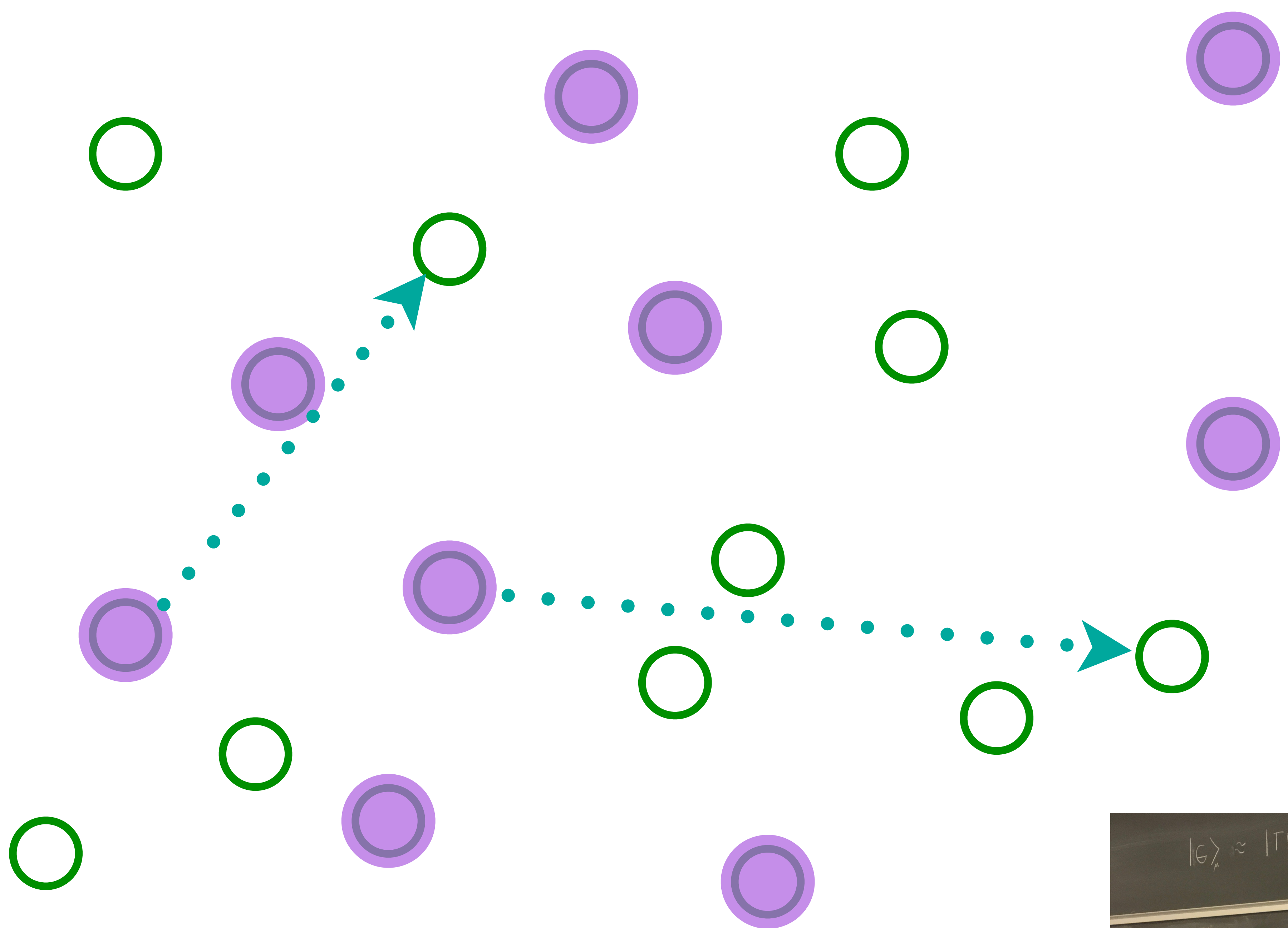
The SYK model



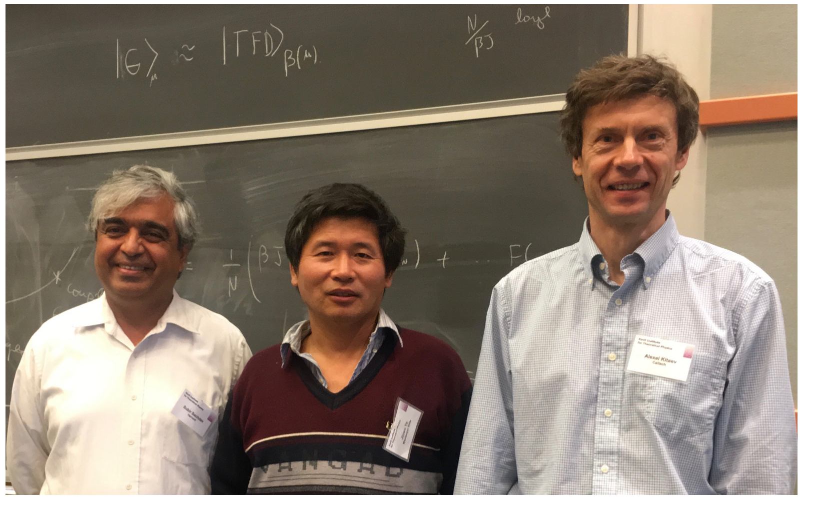


Place electrons randomly on some sites

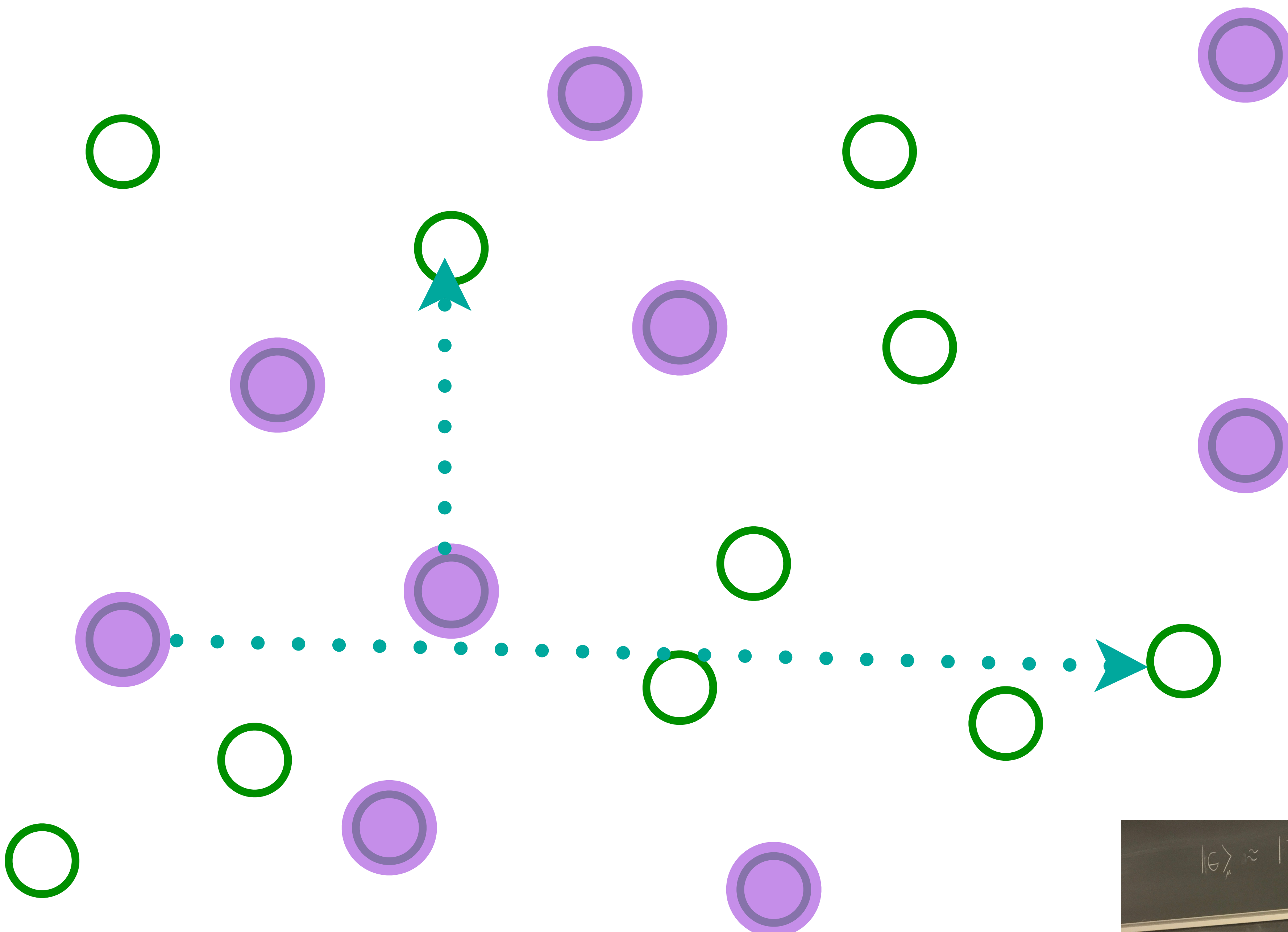
The SYK model



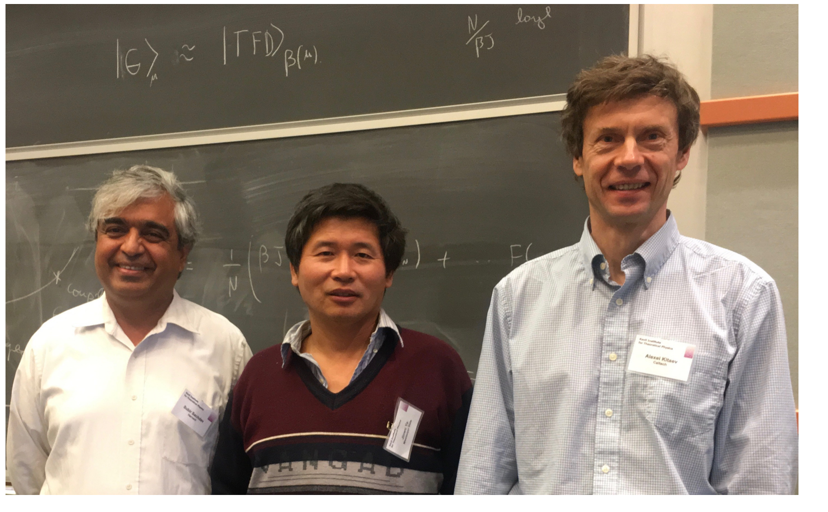
Place electrons randomly on some sites



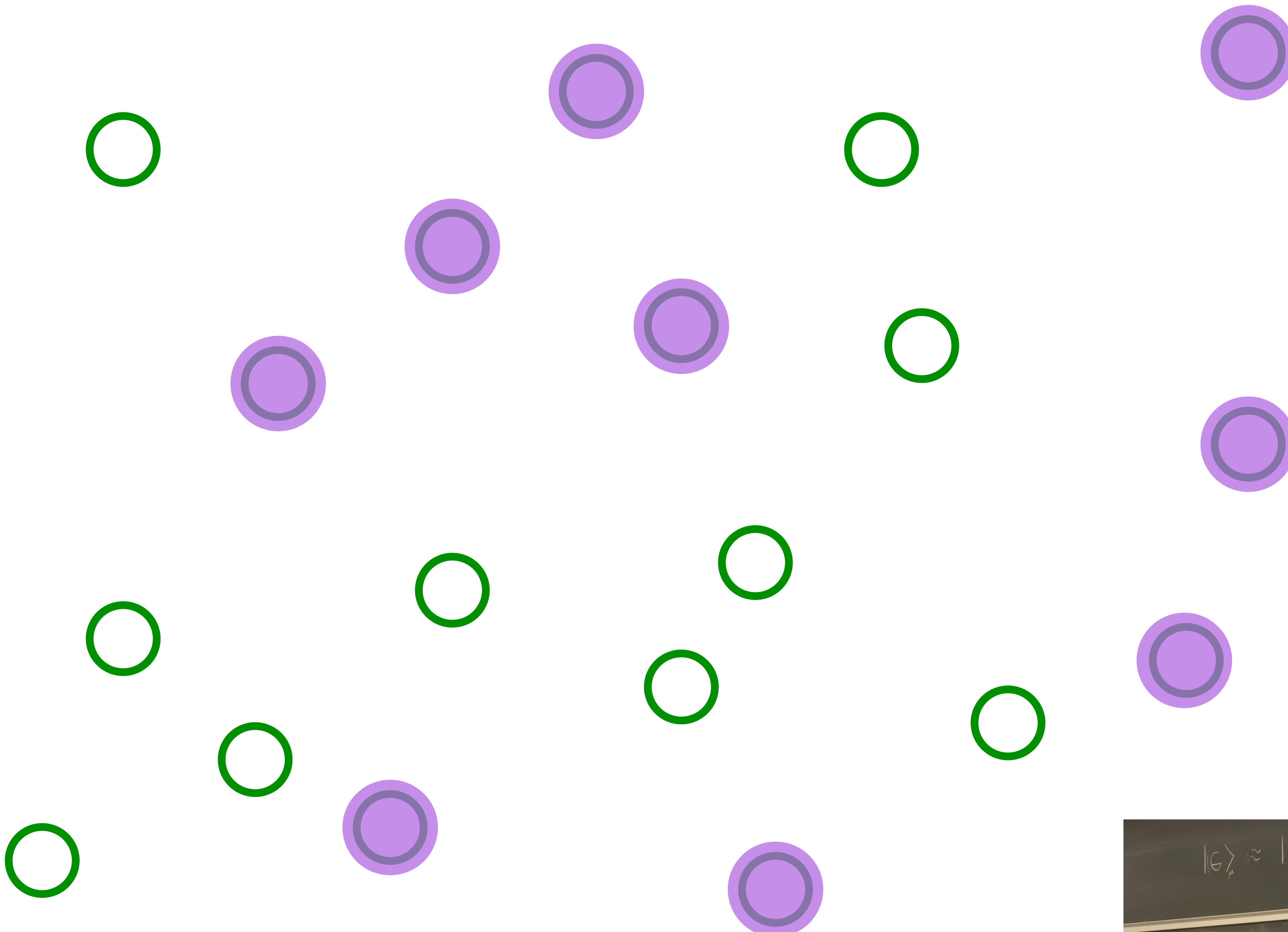
The SYK model



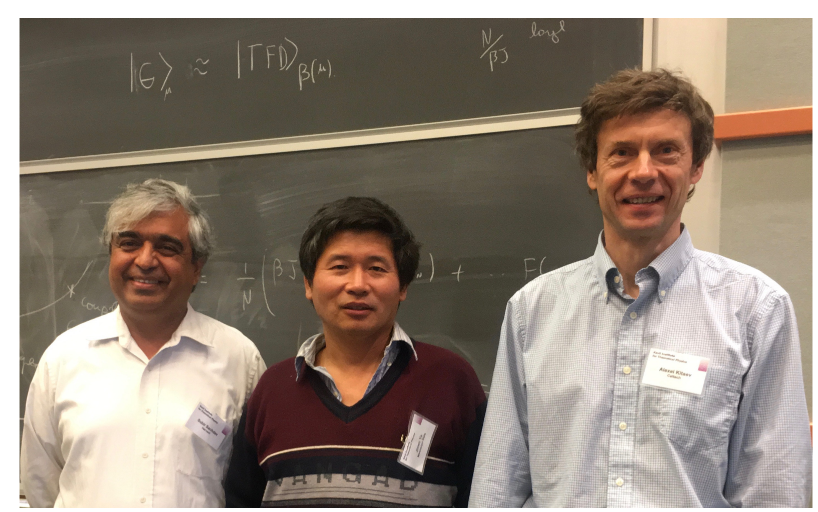
Place electrons randomly on some sites



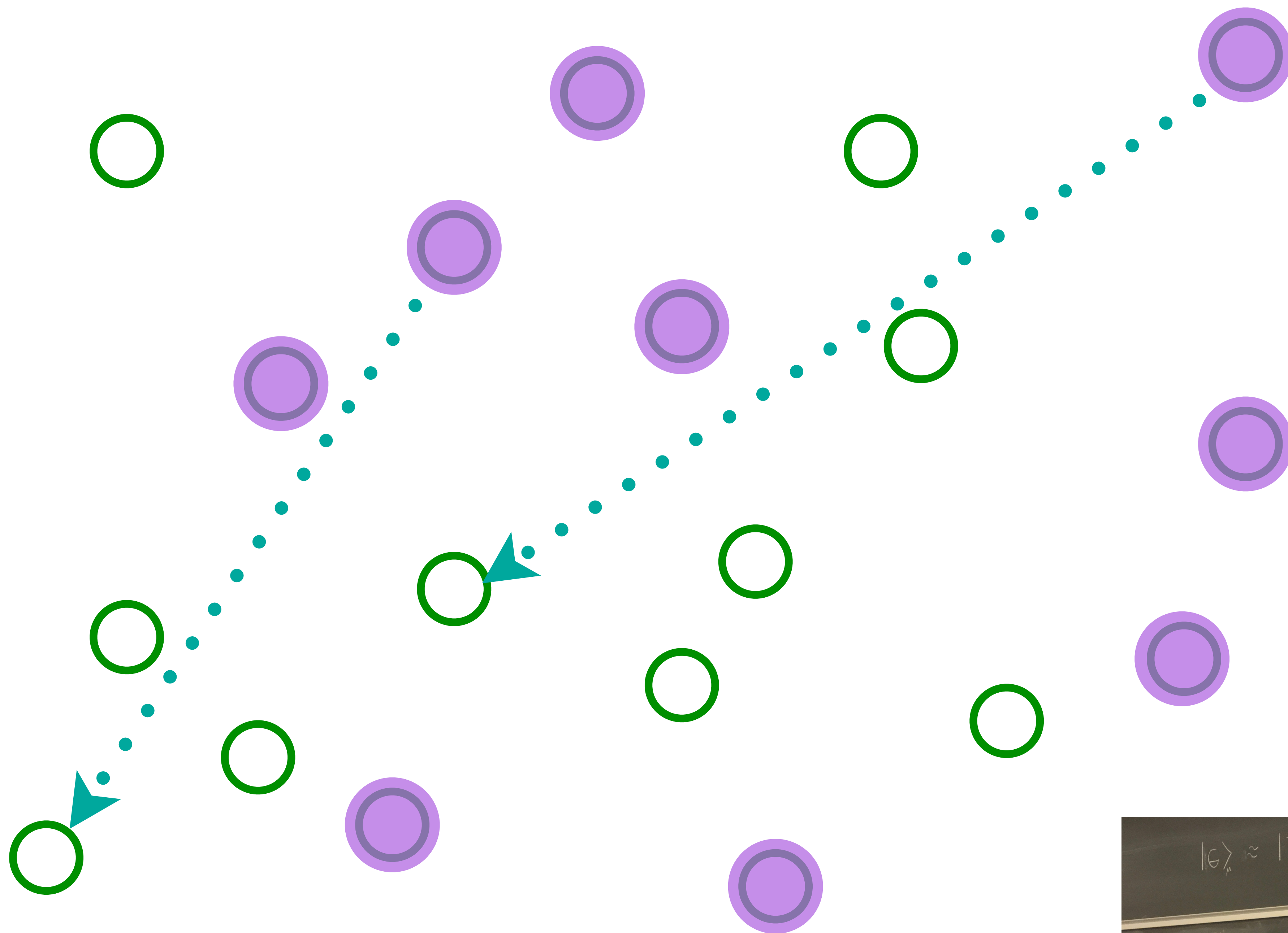
The SYK model



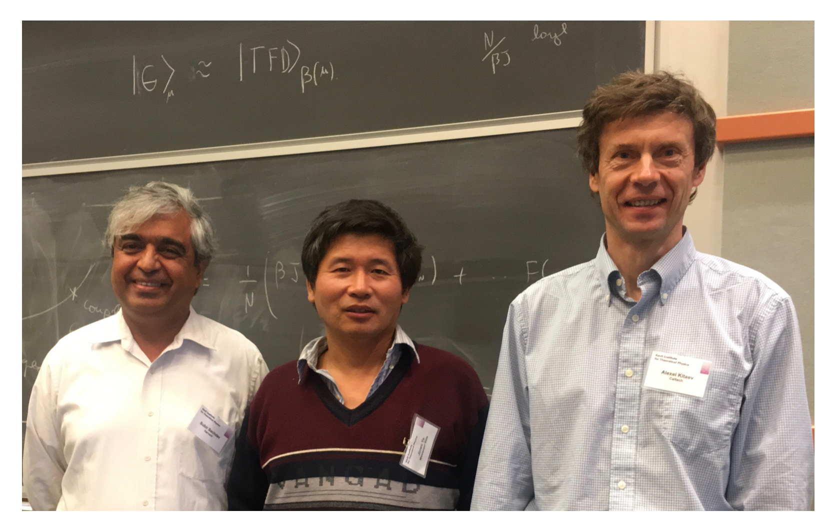
Entangle electrons pairwise randomly



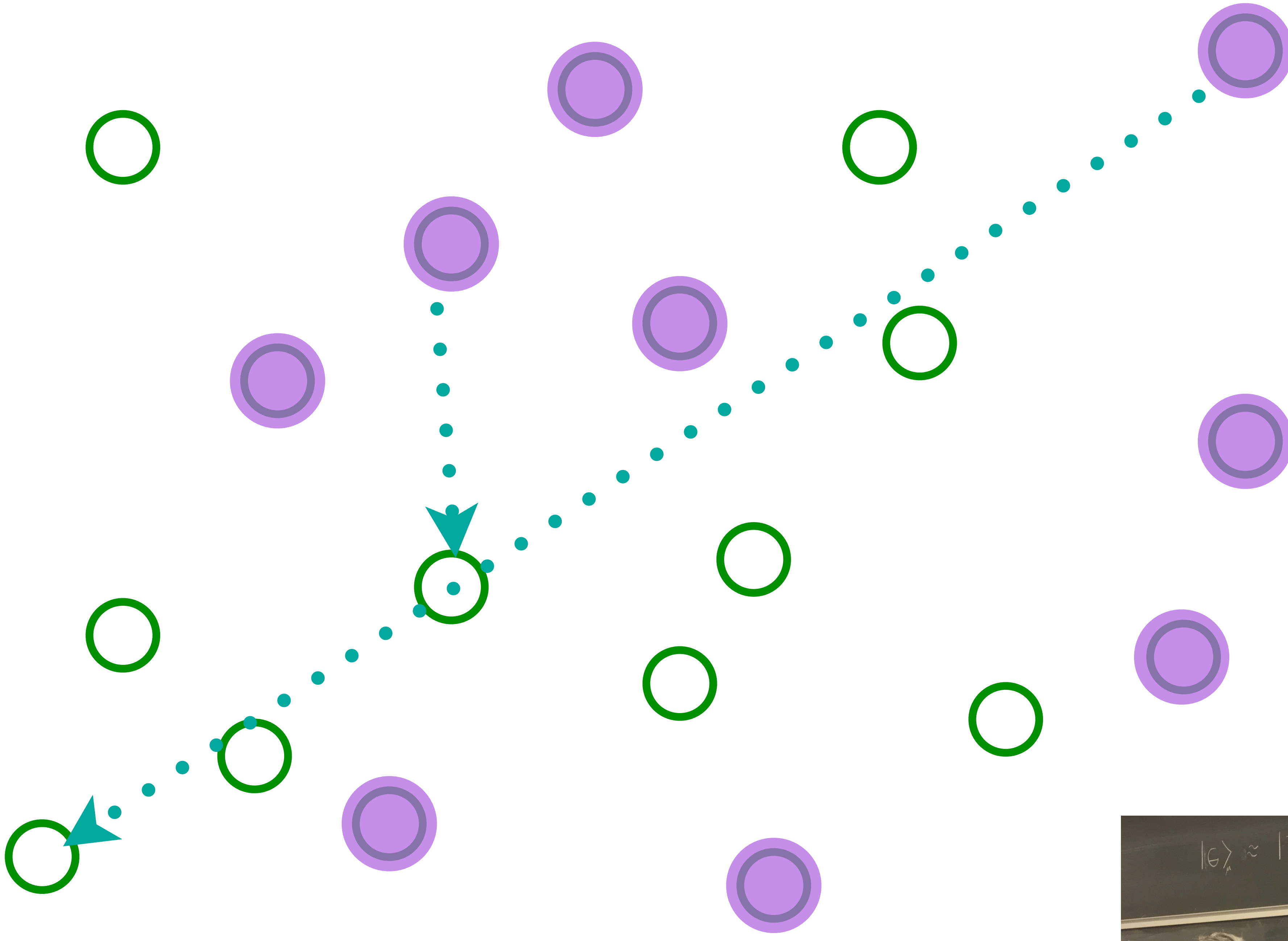
The SYK model



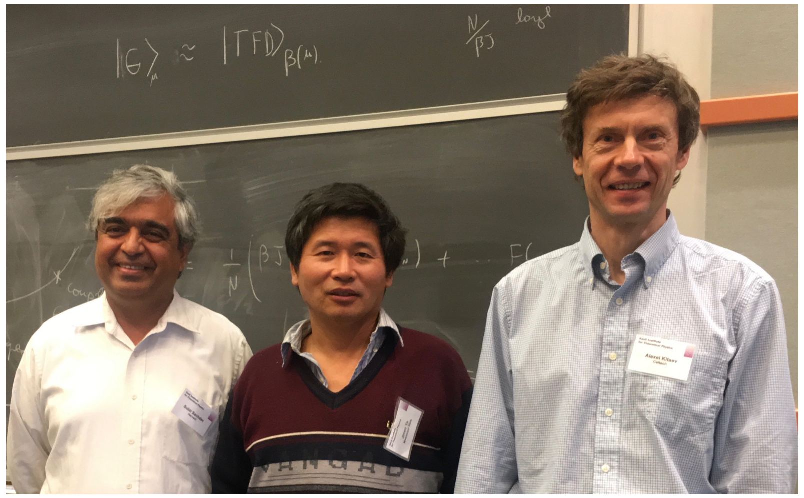
Entangle electrons pairwise randomly



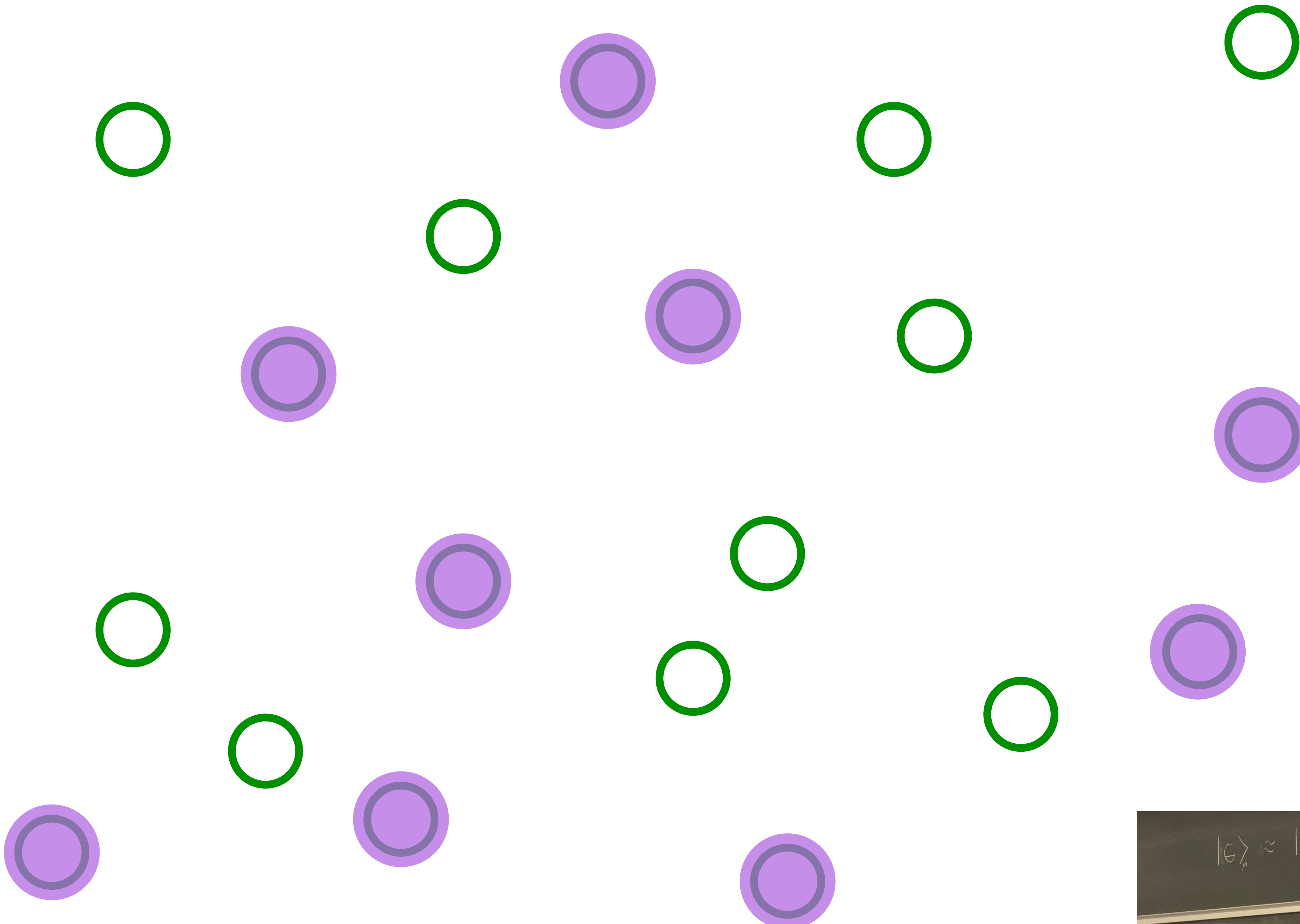
The SYK model



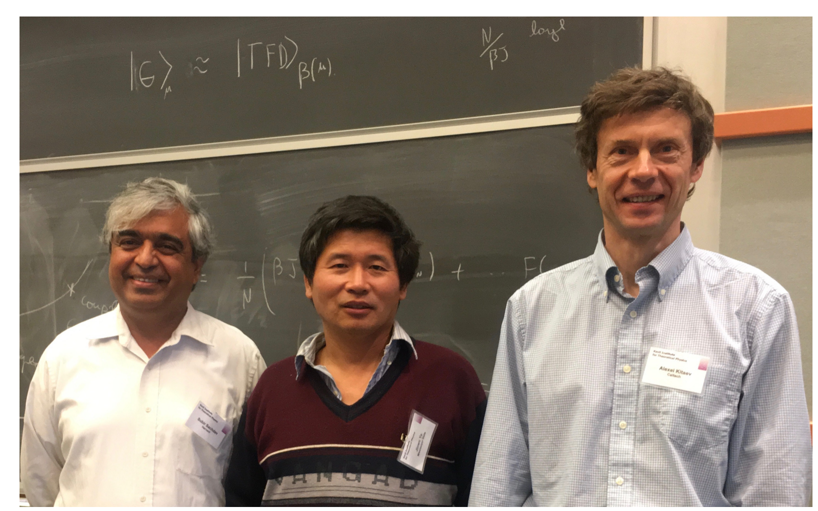
Entangle electrons pairwise randomly



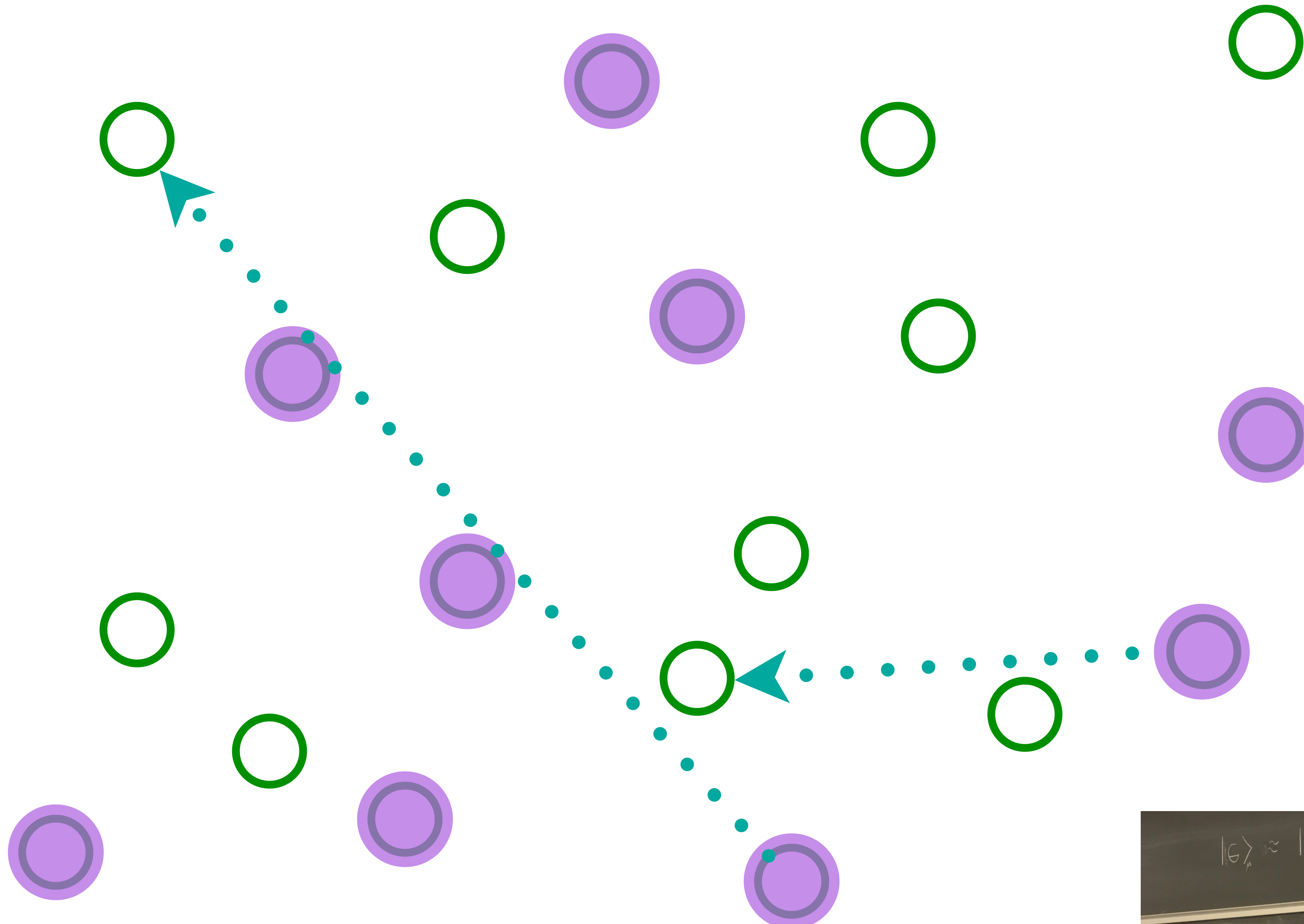
The SYK model



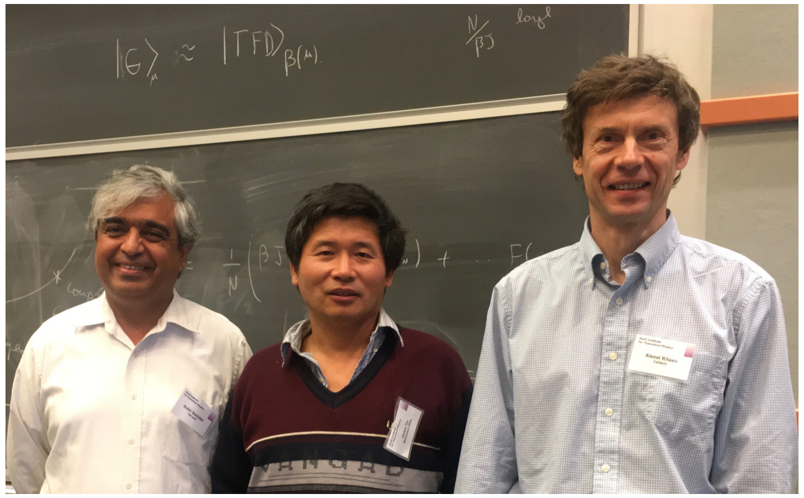
Entangle electrons pairwise randomly



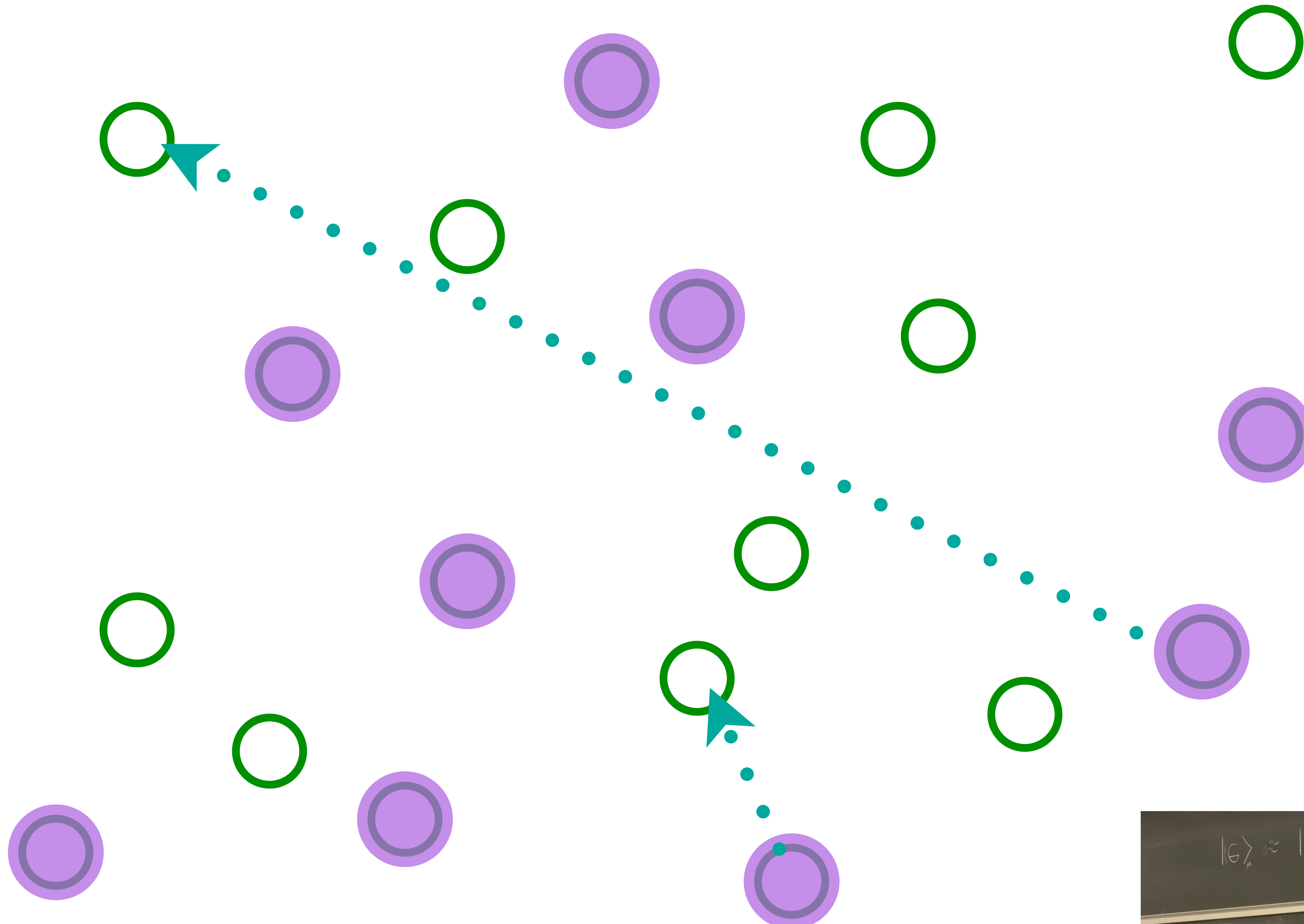
The SYK model



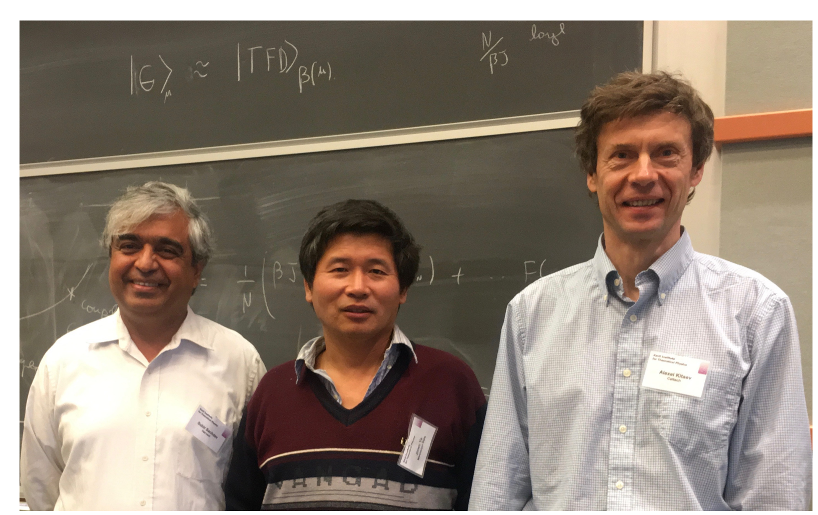
Entangle electrons pairwise randomly



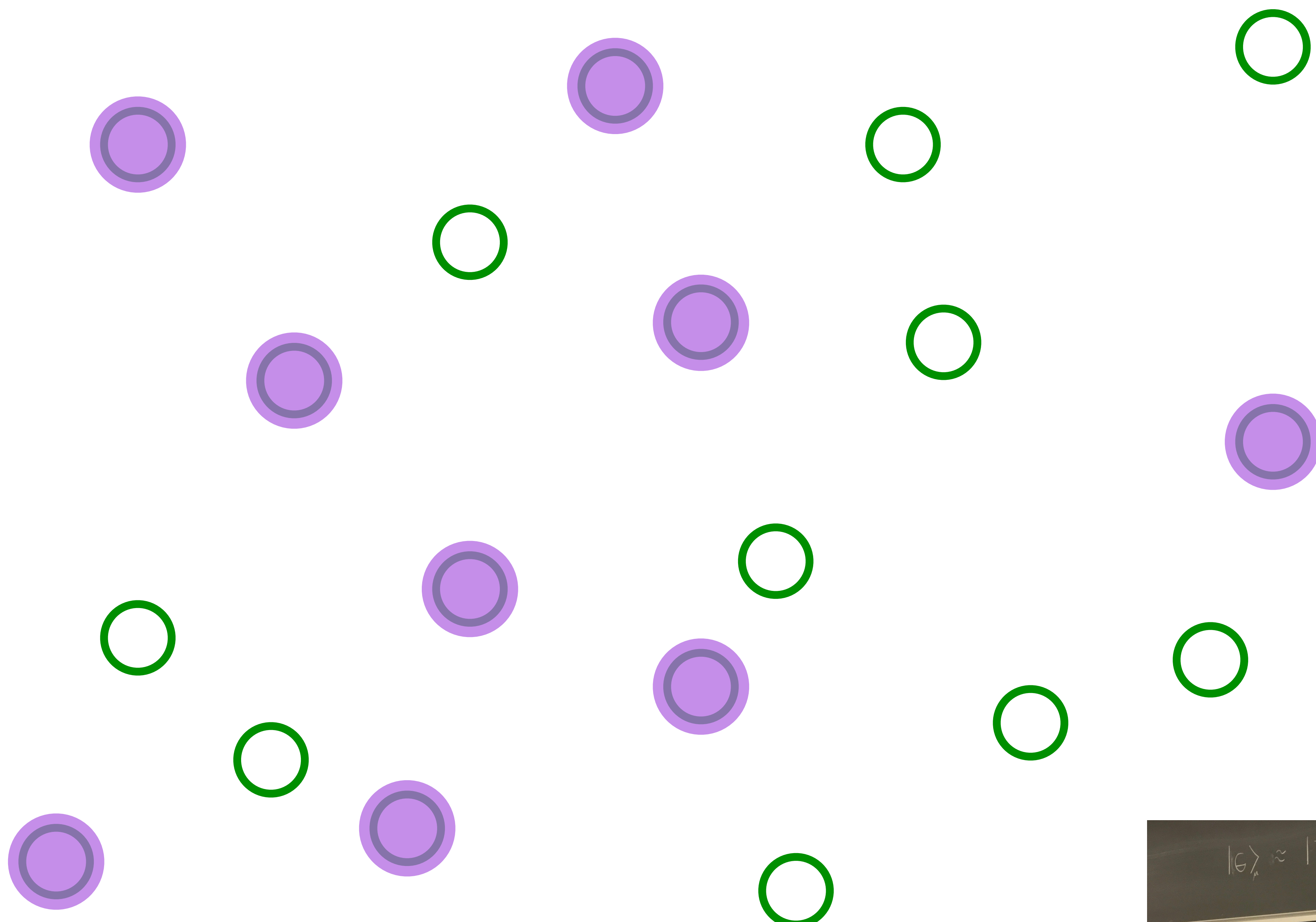
The SYK model



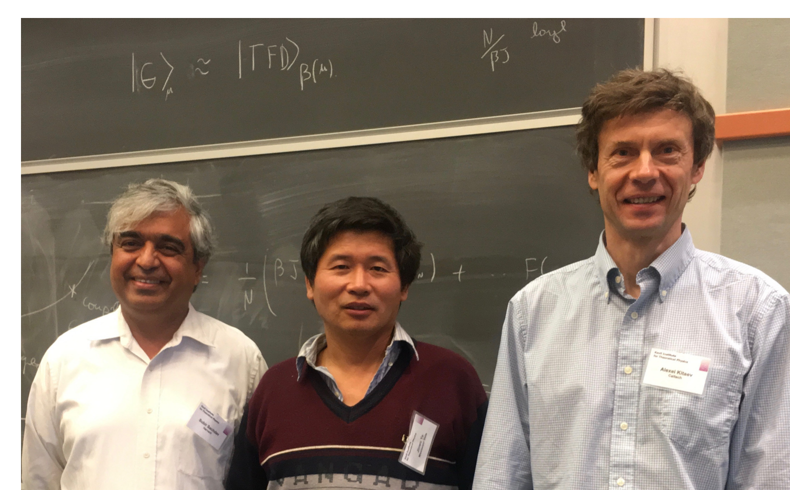
Entangle electrons pairwise randomly



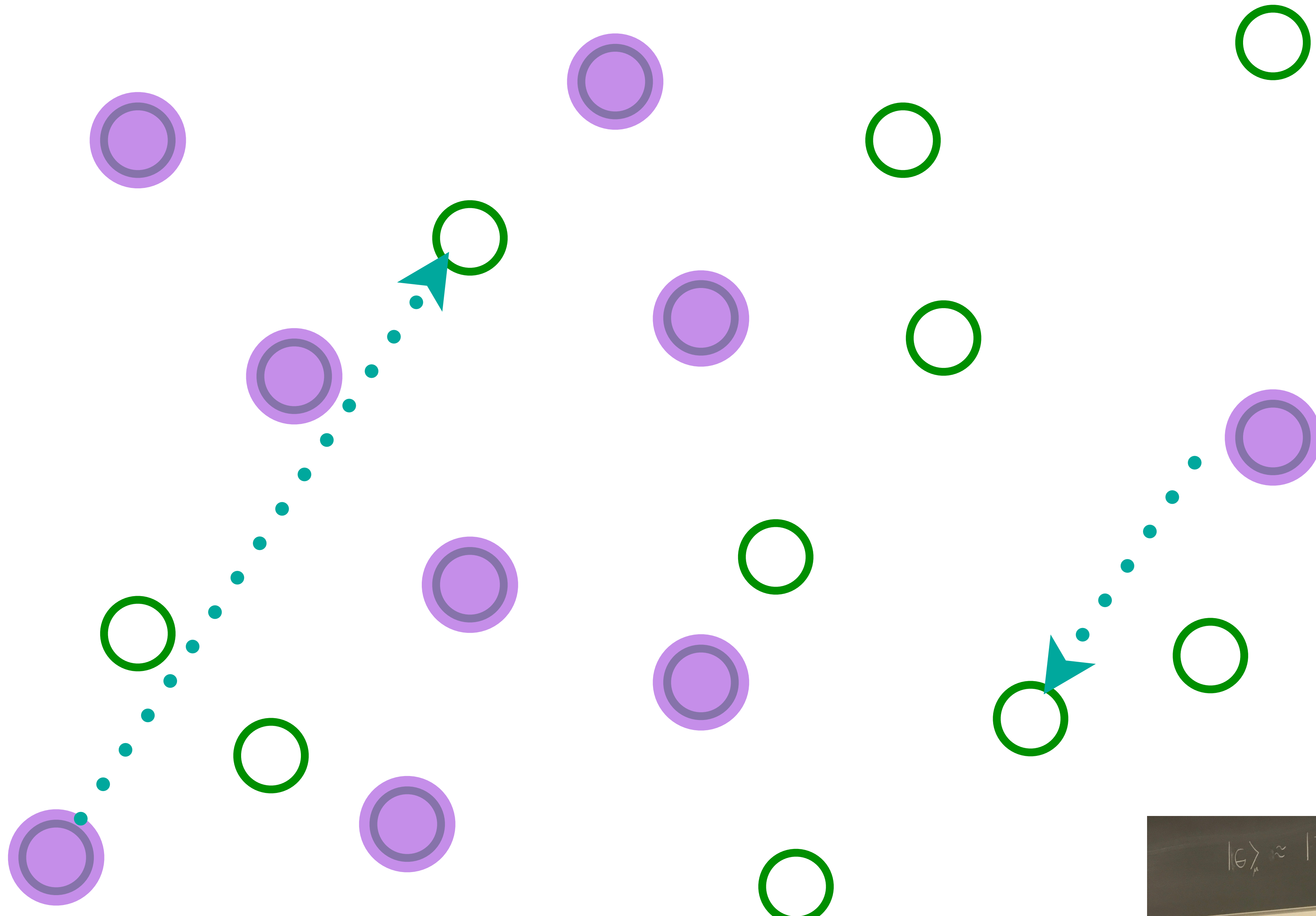
The SYK model



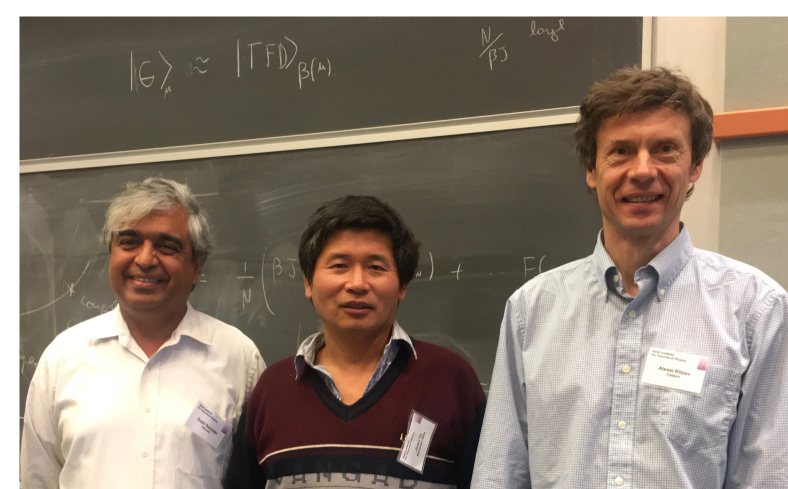
Entangle electrons pairwise randomly



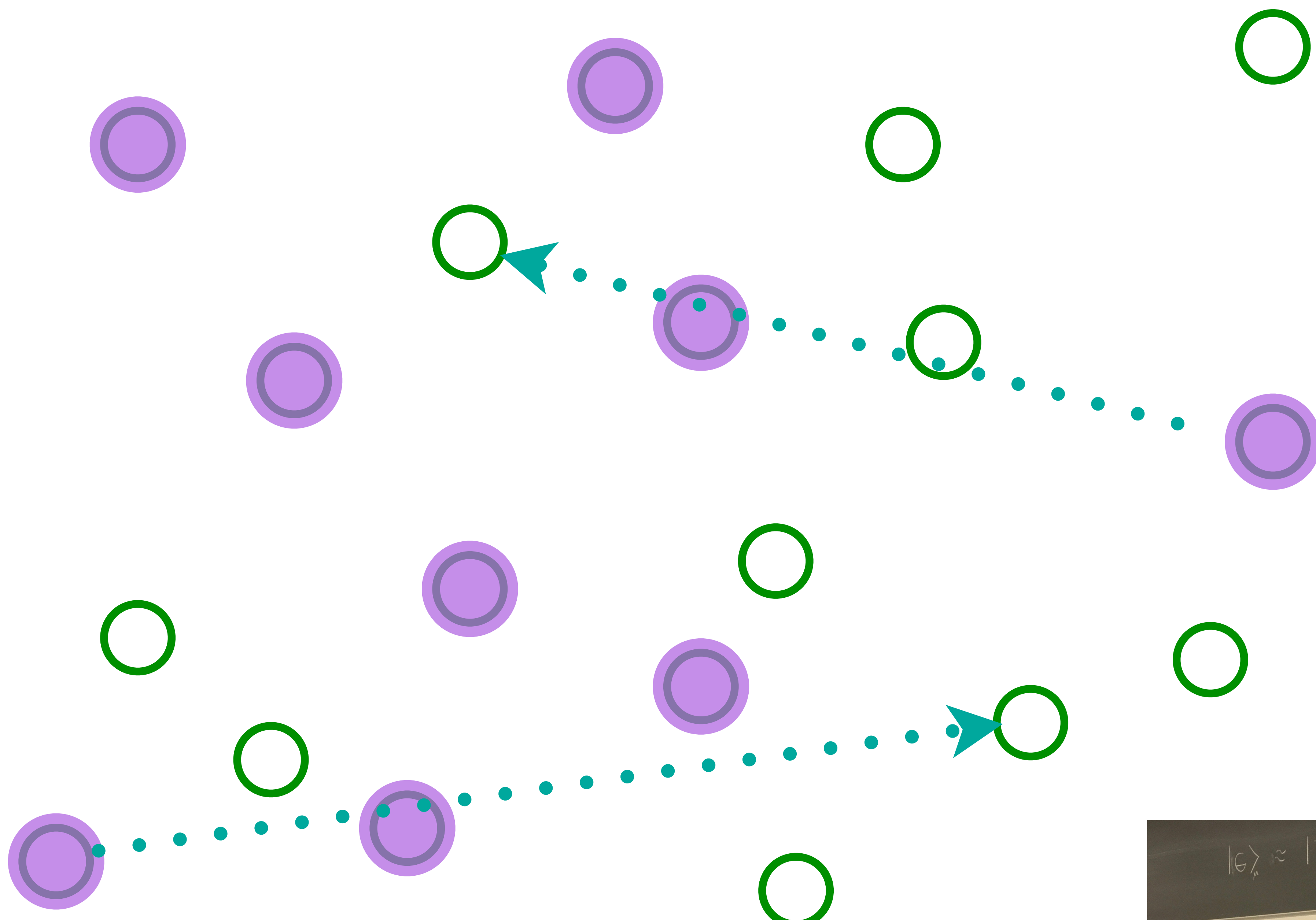
The SYK model



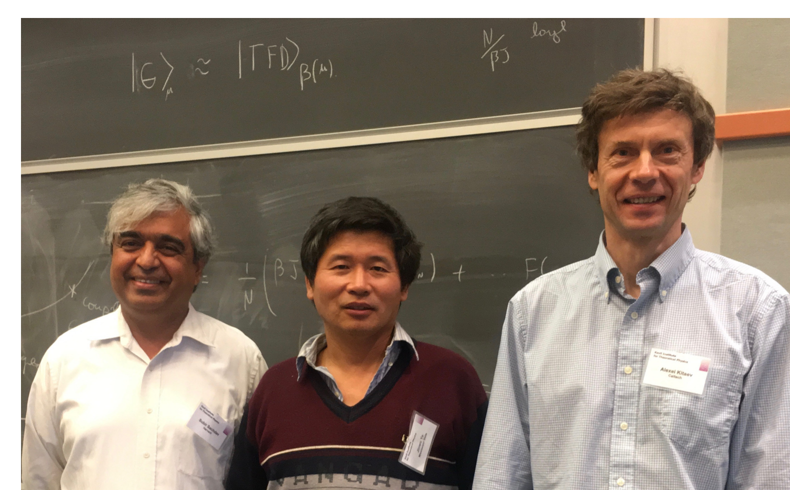
Entangle electrons pairwise randomly



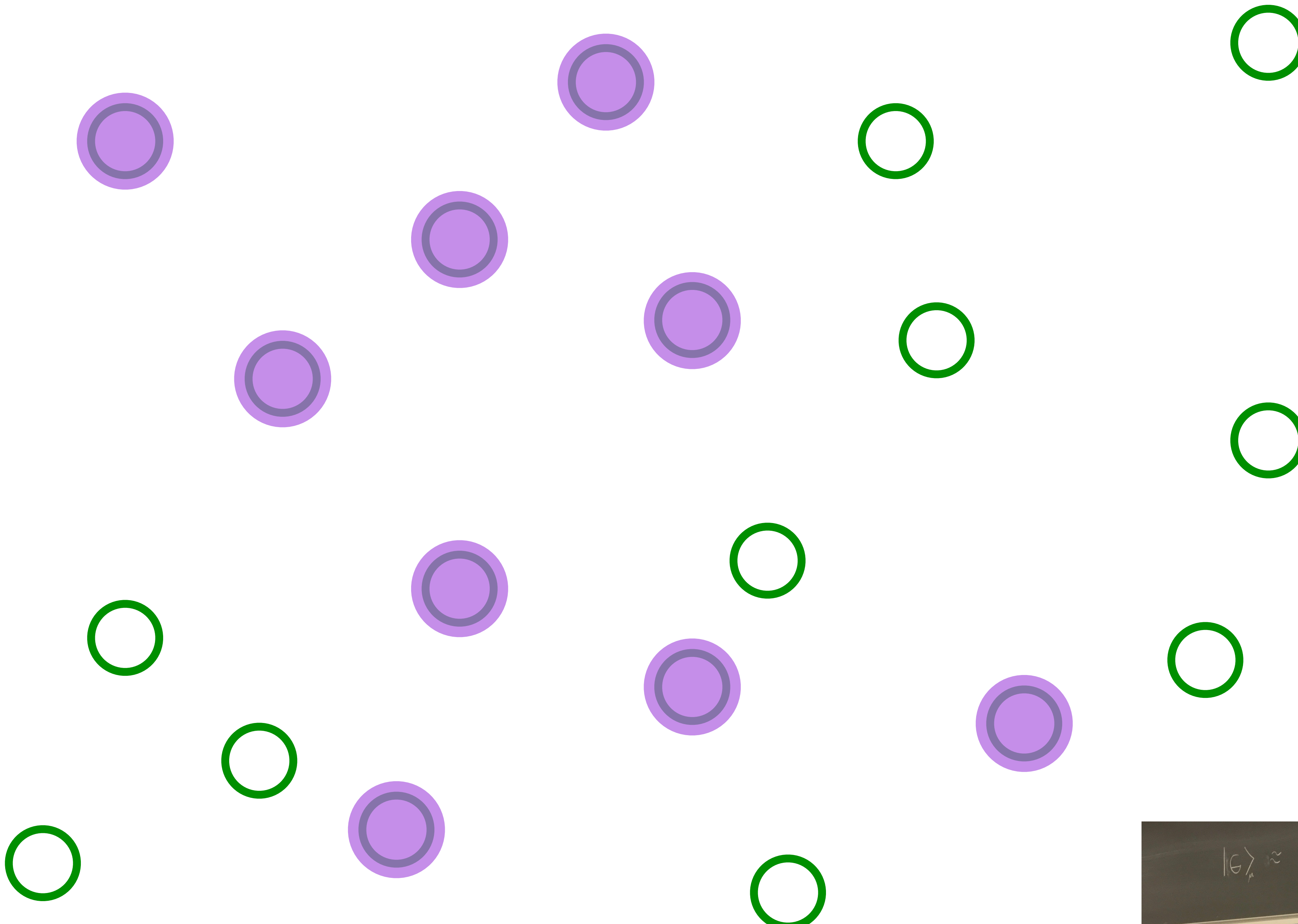
The SYK model



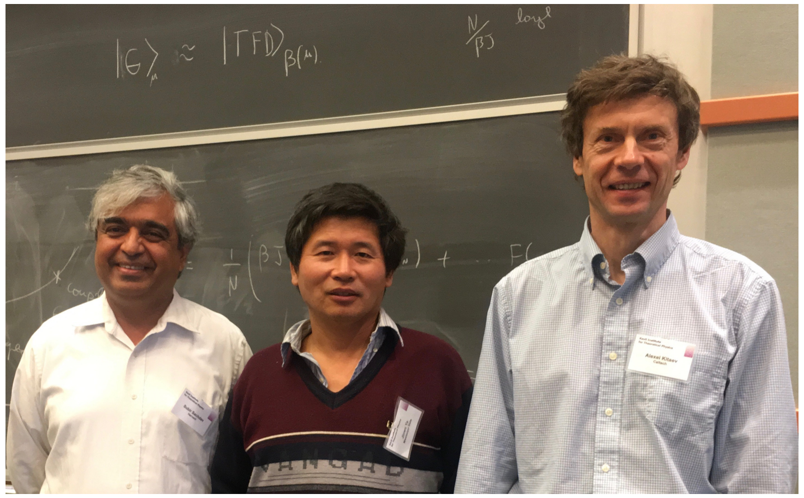
Entangle electrons pairwise randomly



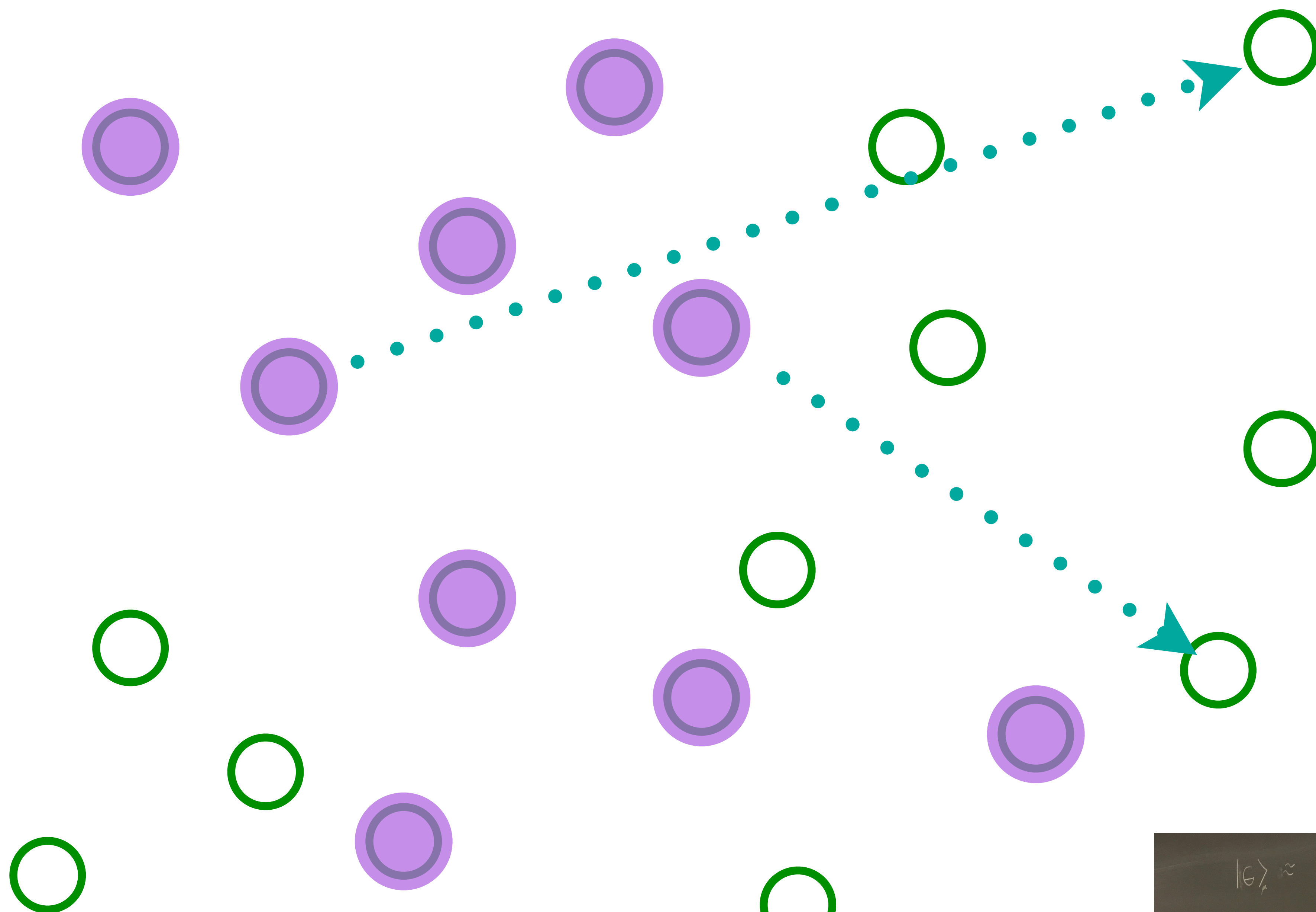
The SYK model



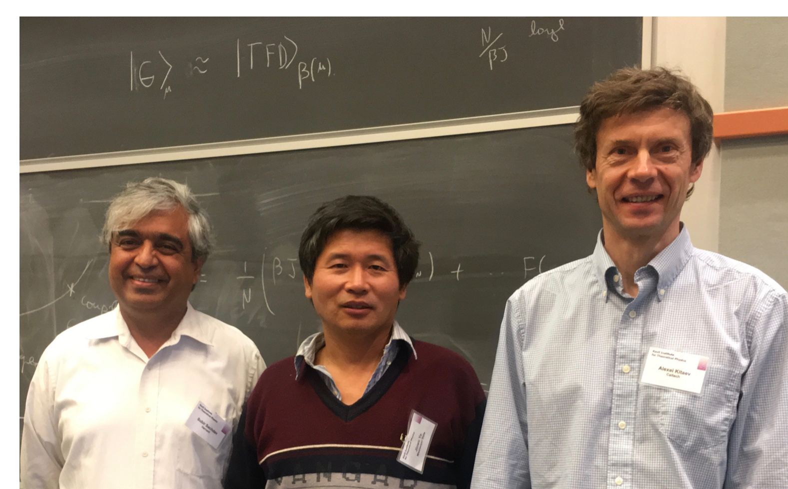
Entangle electrons pairwise randomly



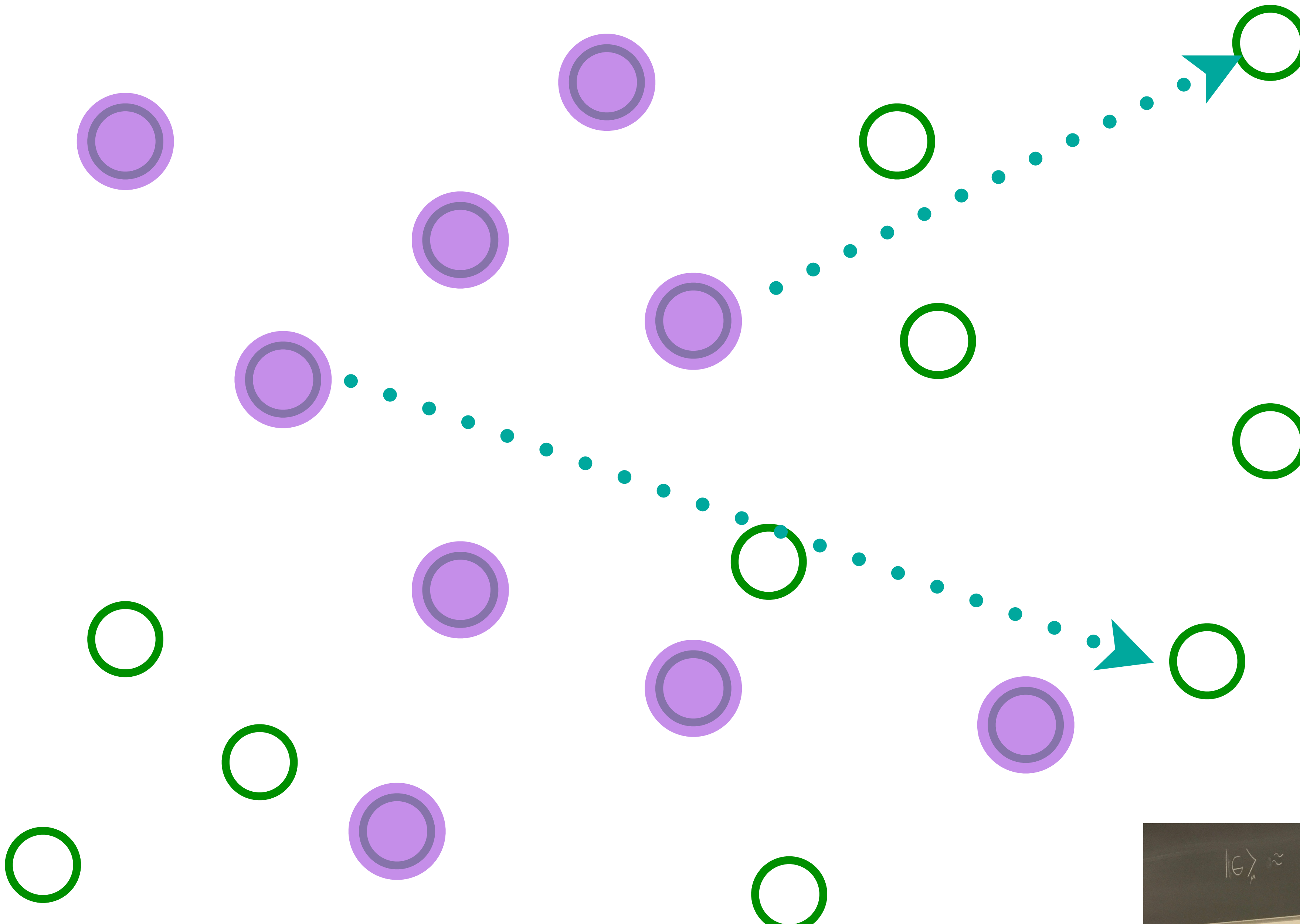
The SYK model



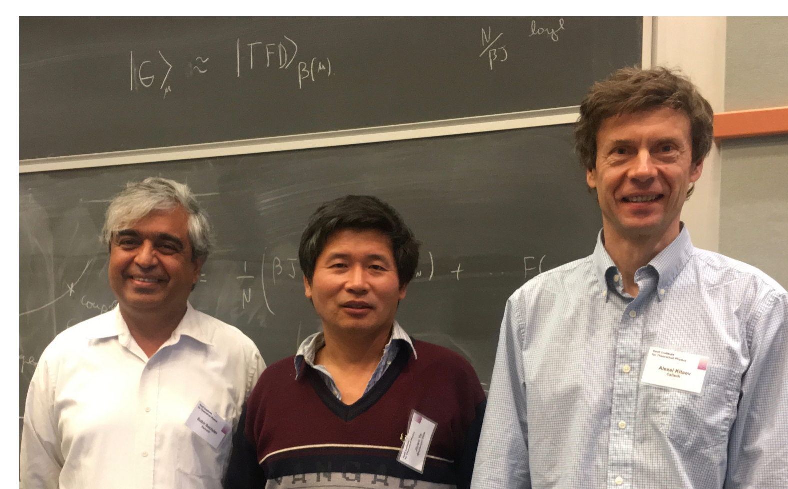
Entangle electrons pairwise randomly



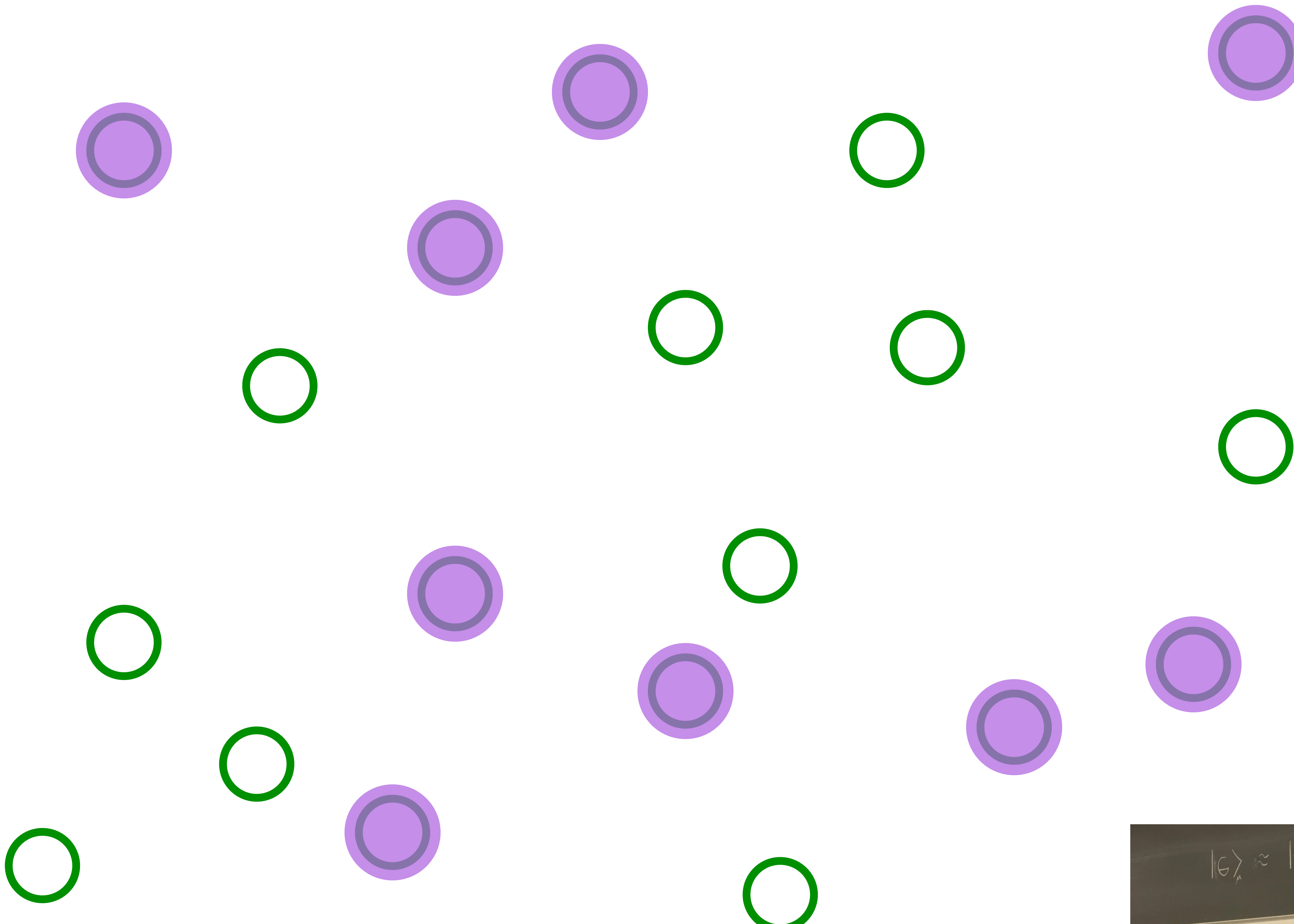
The SYK model



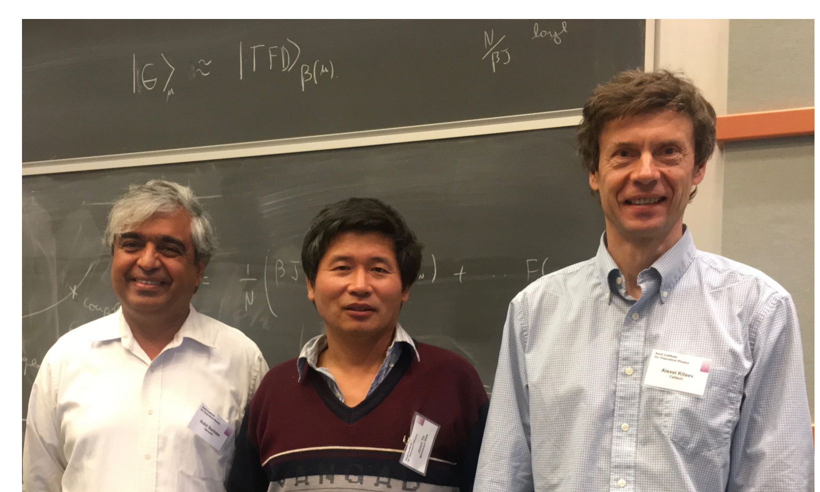
Entangle electrons pairwise randomly



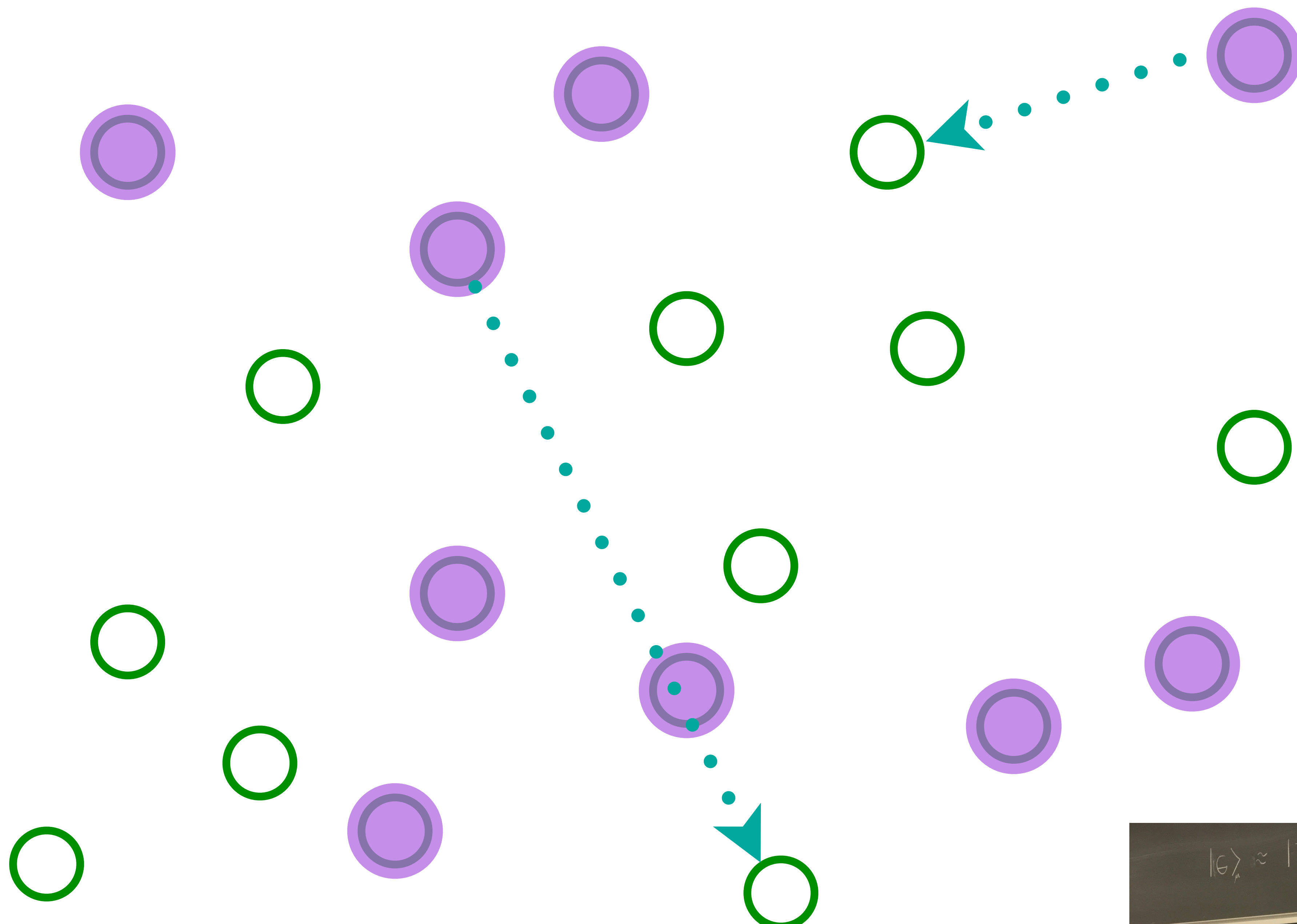
The SYK model



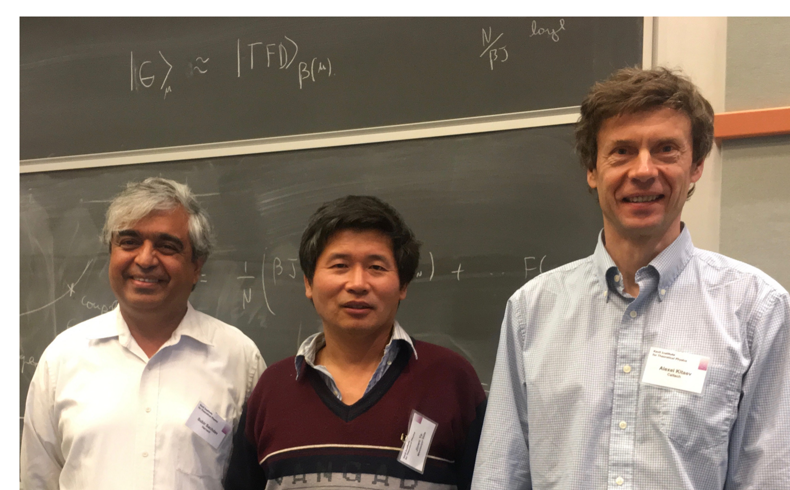
Entangle electrons pairwise randomly



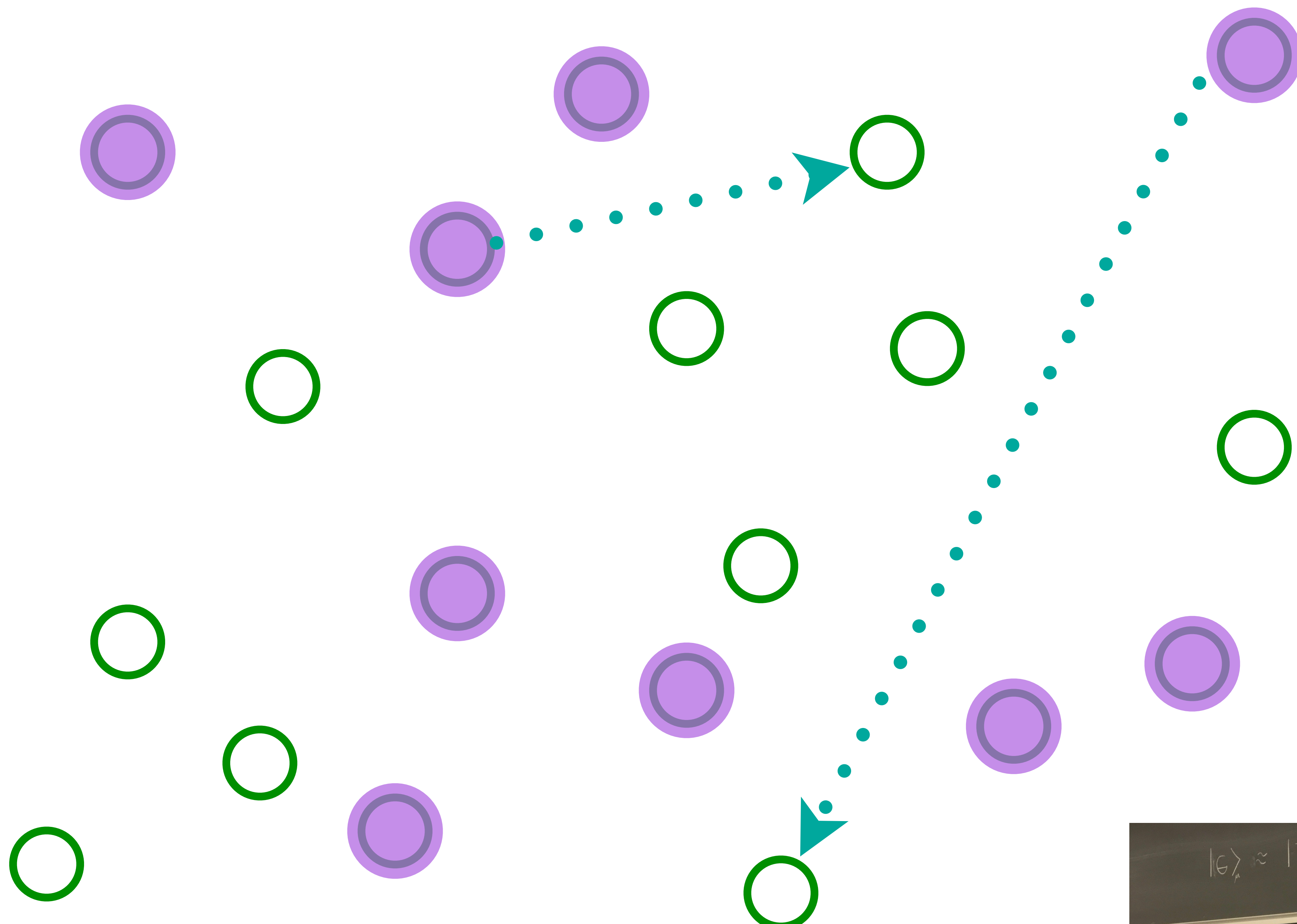
The SYK model



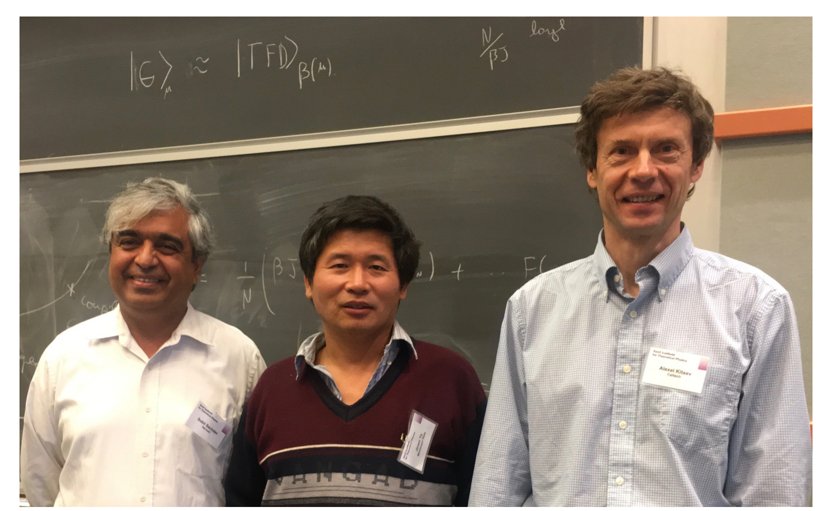
Entangle electrons pairwise randomly



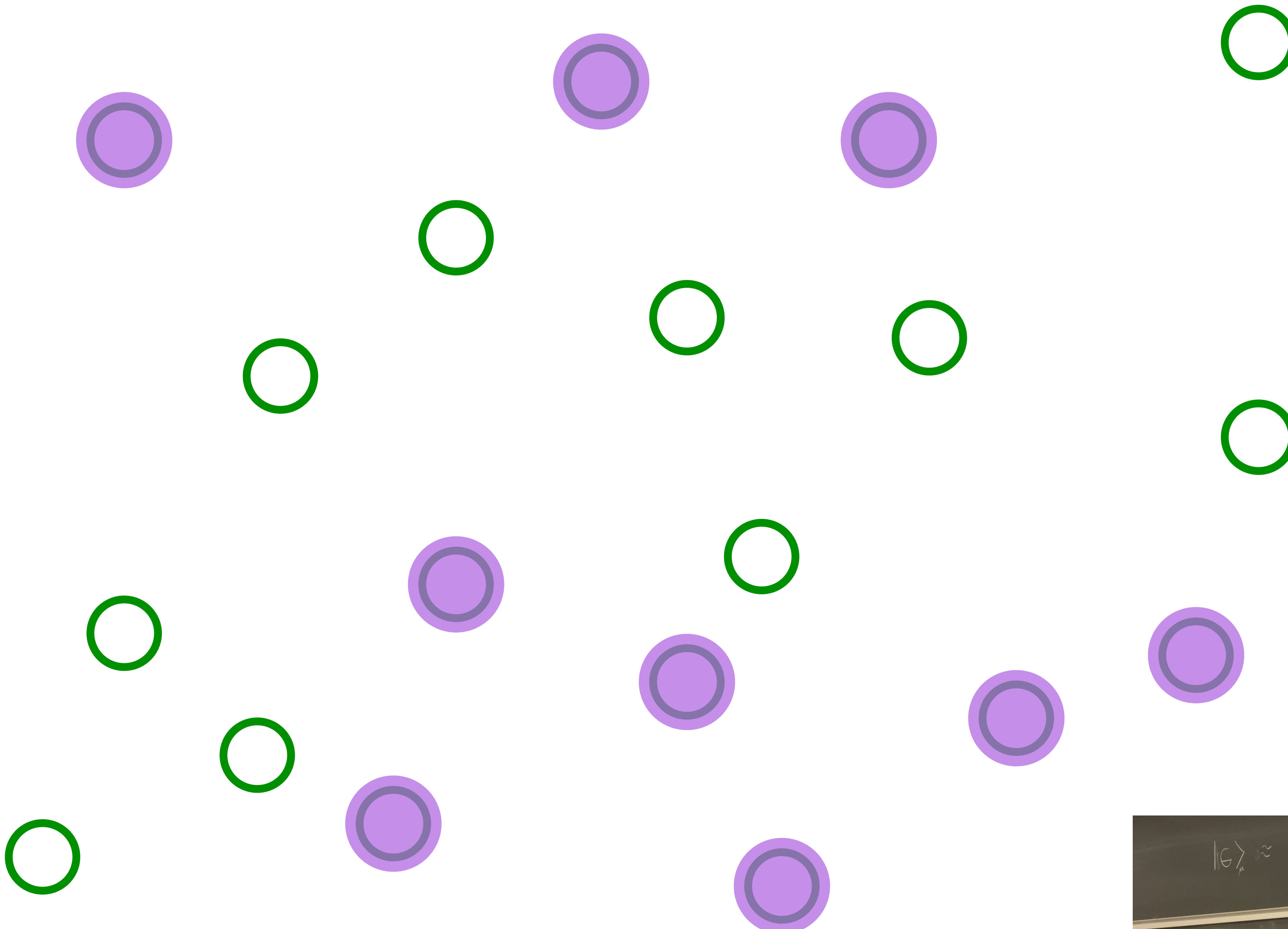
The SYK model



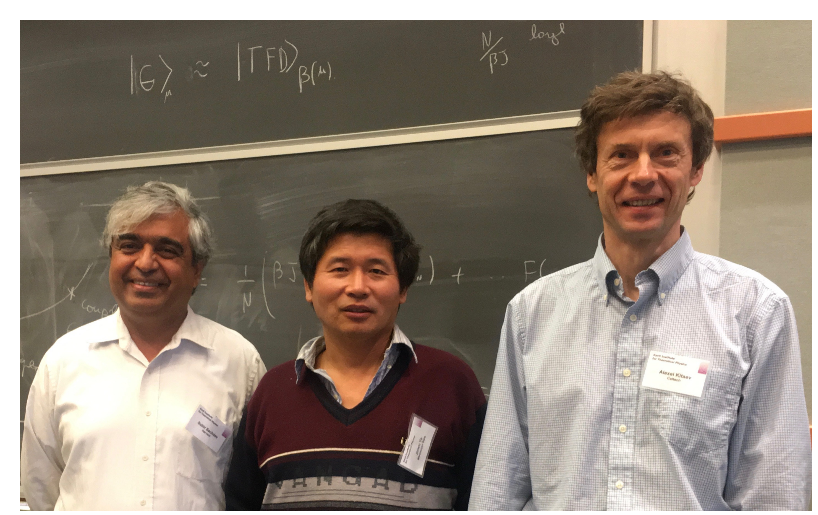
Entangle electrons pairwise randomly



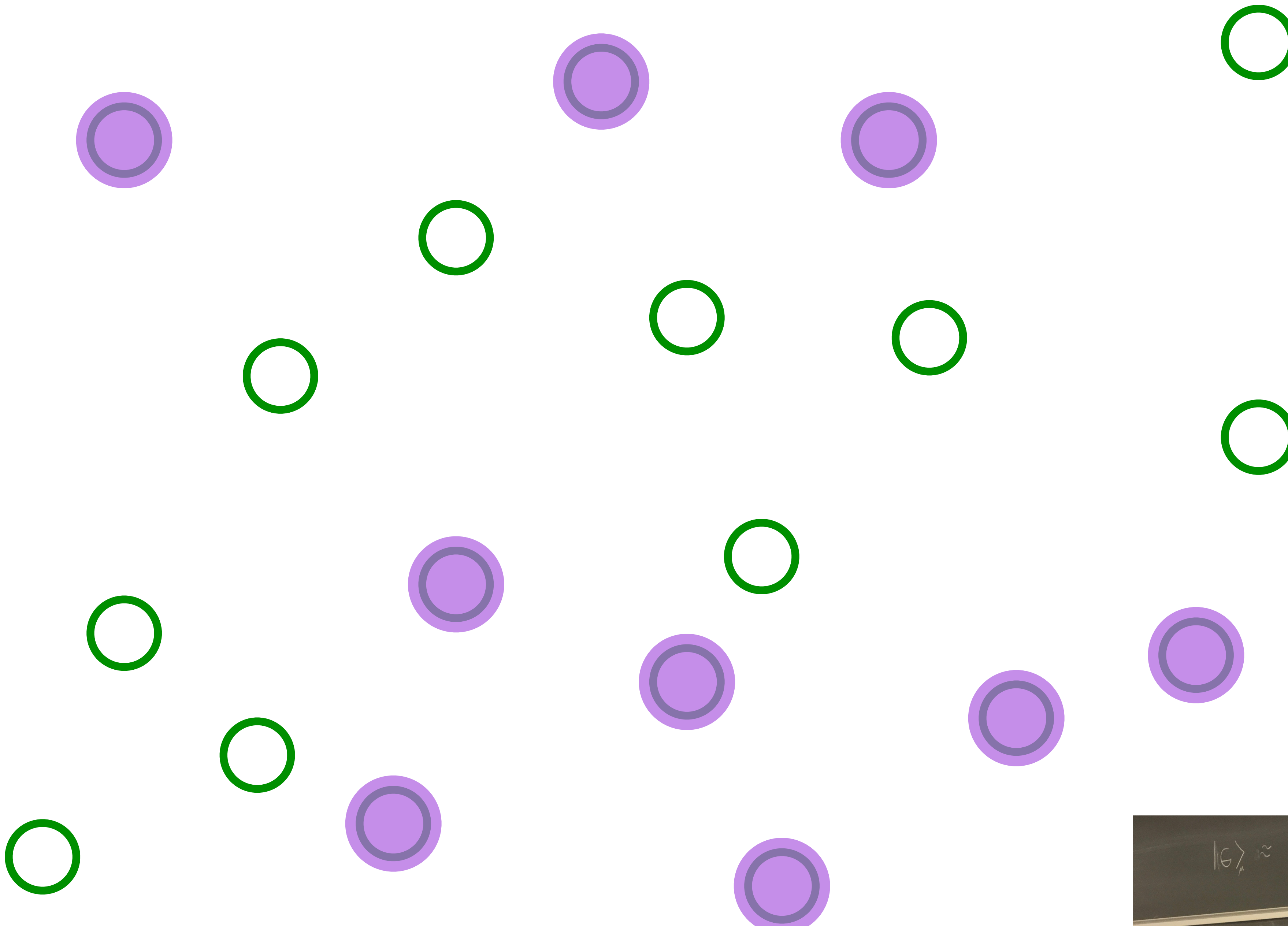
The SYK model



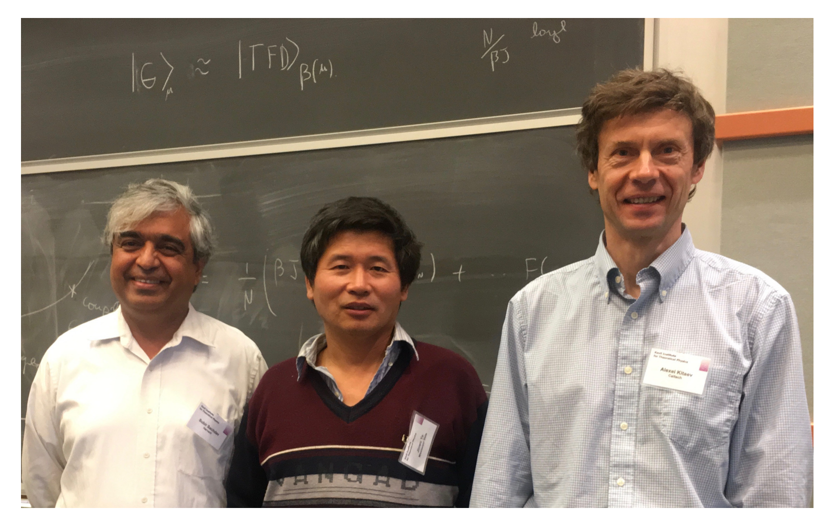
Entangle electrons pairwise randomly



The SYK model



This describes both a strange metal and a black hole!



The SYK model

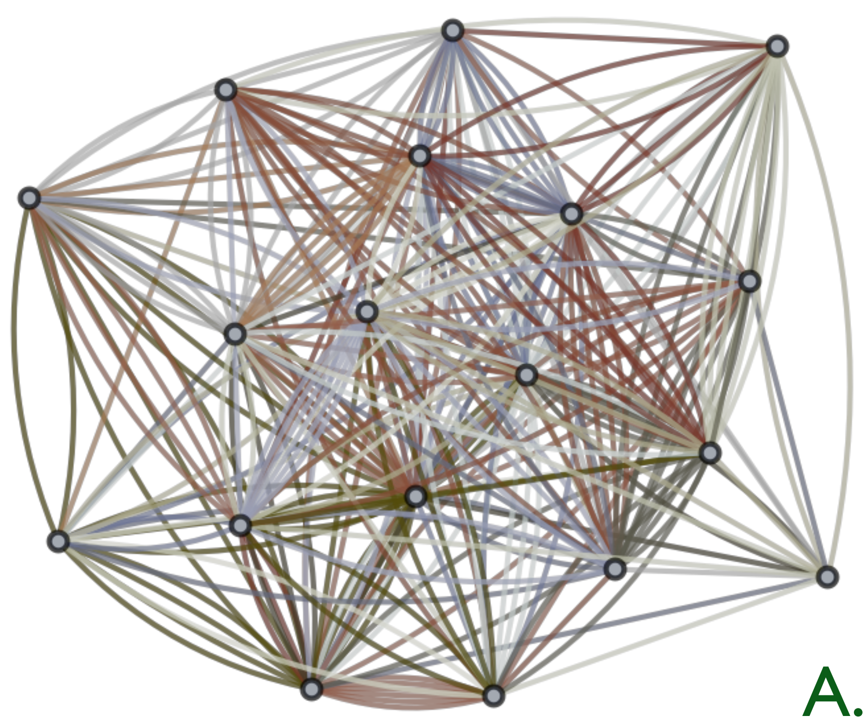
(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large *N* limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} U_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell + e \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$

$U_{ij;k\ell}$ are independent random variables with $\overline{U_{ij;k\ell}} = 0$ and $\overline{|U_{ij;k\ell}|^2} = U^2$
$N \to \infty$ yields critical strange metal.

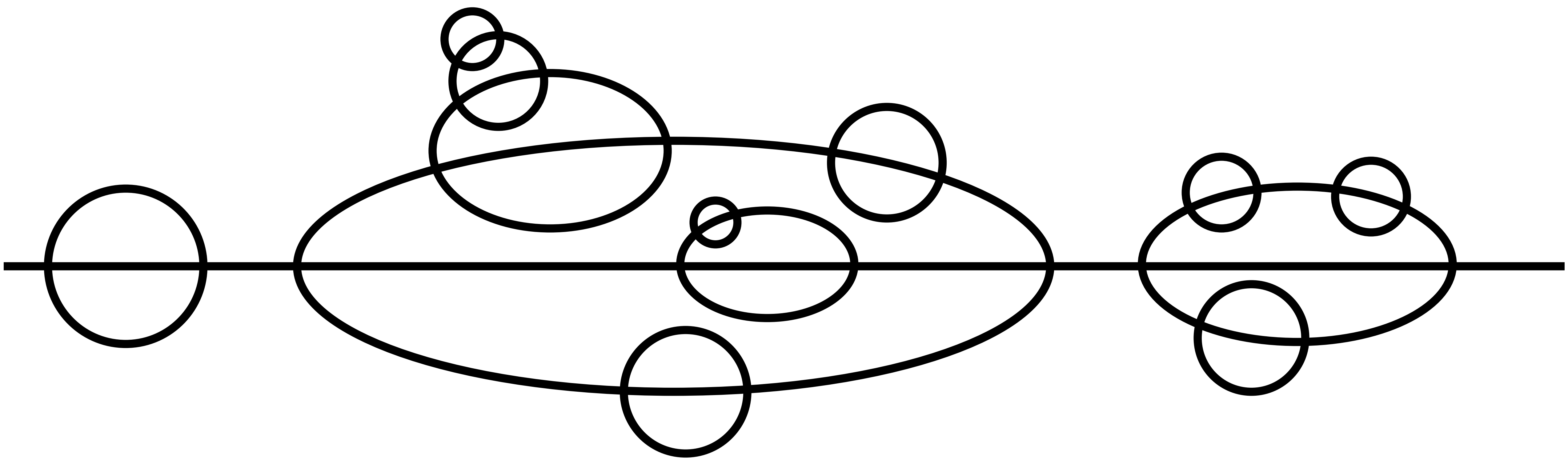


S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

The SYK model

The large N limit is given by the sum of "melon" Feynman graphs



S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

The SYK model

The large N limit is given by the sum of "melon" Feynman graphs

For long times $\tau > 0$

$$\left\langle c_i(\tau) c_i^\dagger(0) \right\rangle = \frac{A}{\sqrt{\tau}}$$

$$\left\langle c_i^\dagger(\tau) c_i(0) \right\rangle = e^{-2\pi\mathcal{E}} \frac{A}{\sqrt{\tau}}$$

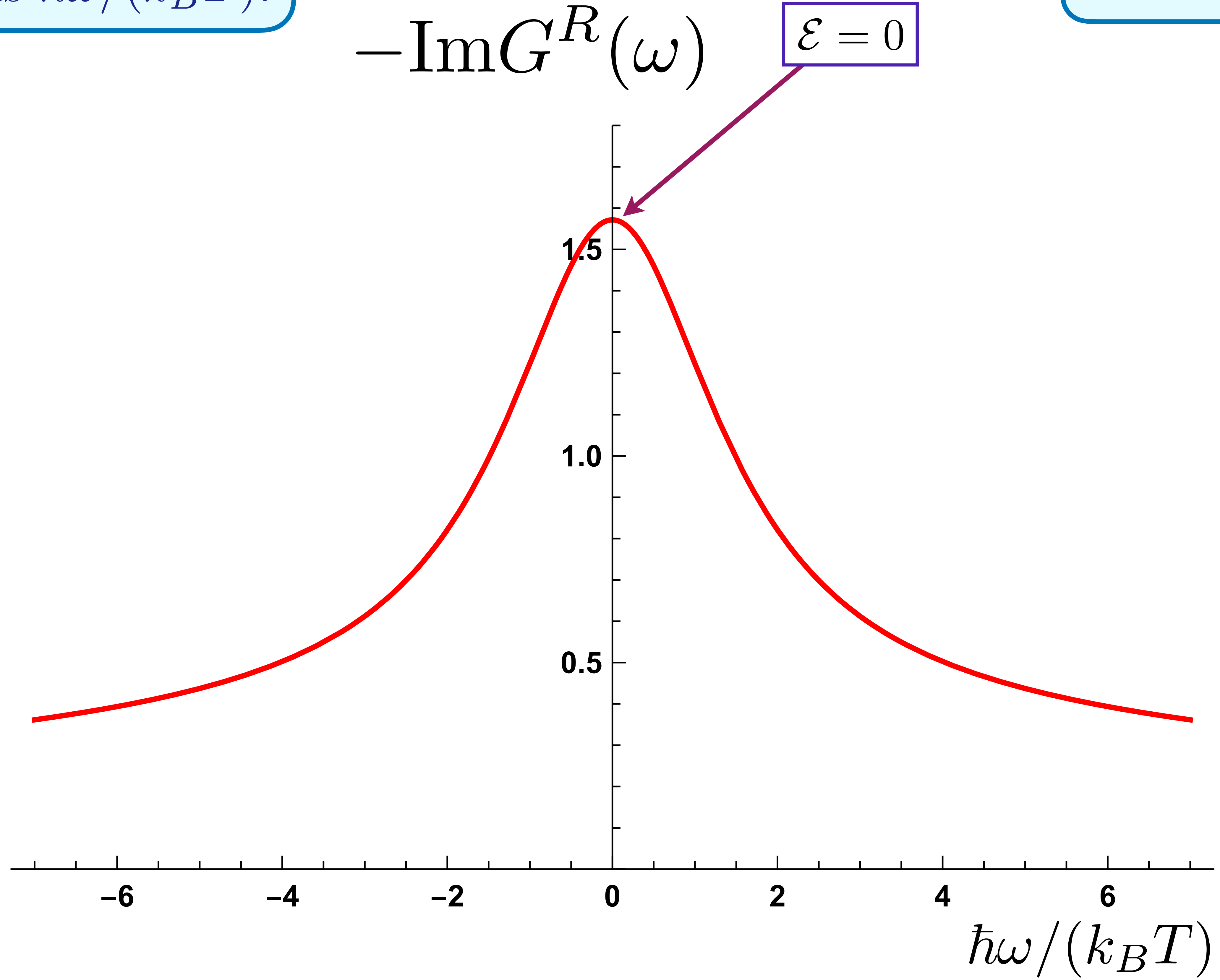
The parameter $\mathcal{E}$ determines the particle-hole asymmetry.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

The complex SYK model

ω dependence of G^R scales as $\hbar\omega/(k_B T)$.

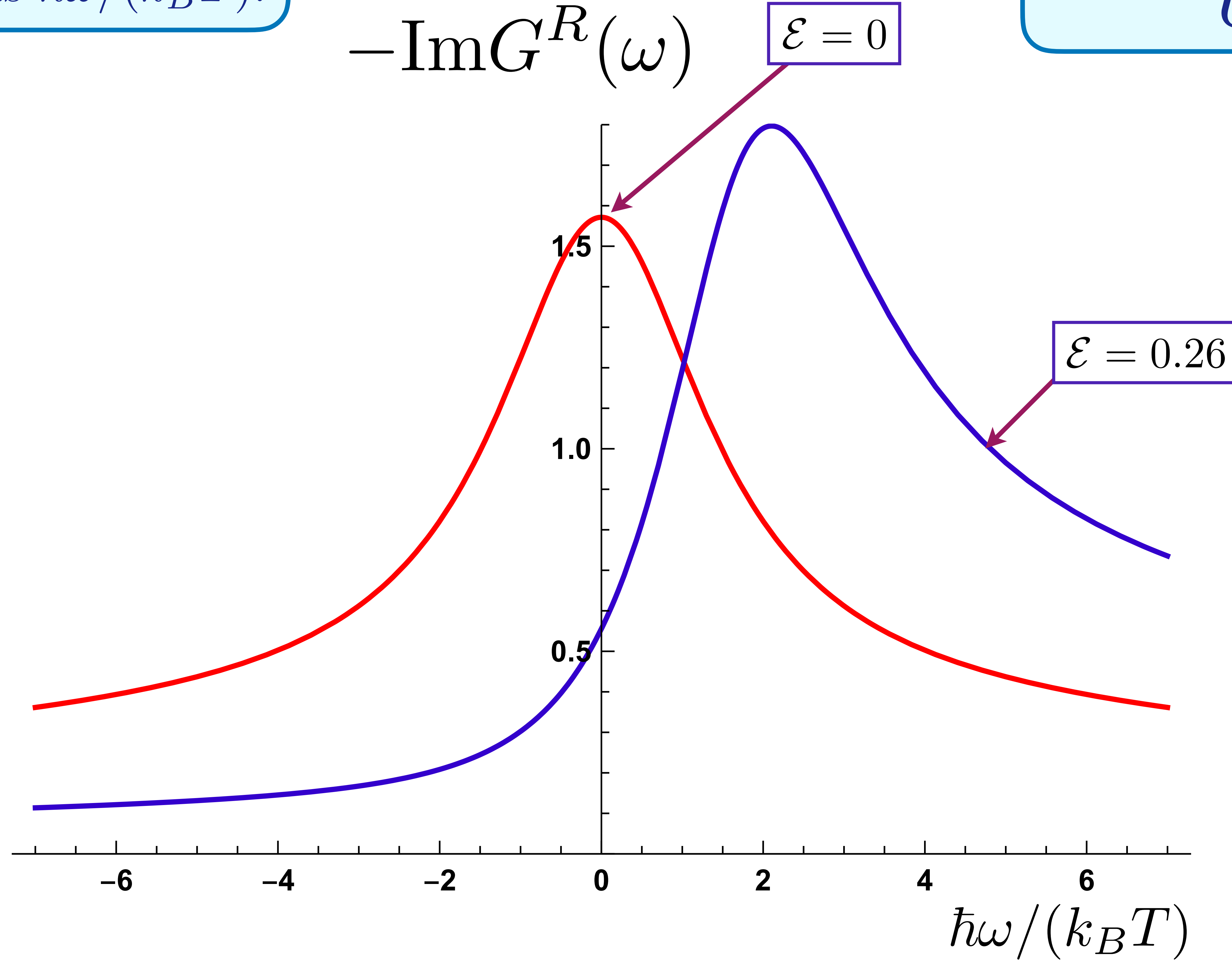
$e = 0$



The complex SYK model

ω dependence of G^R scales as $\hbar\omega/(k_B T)$.

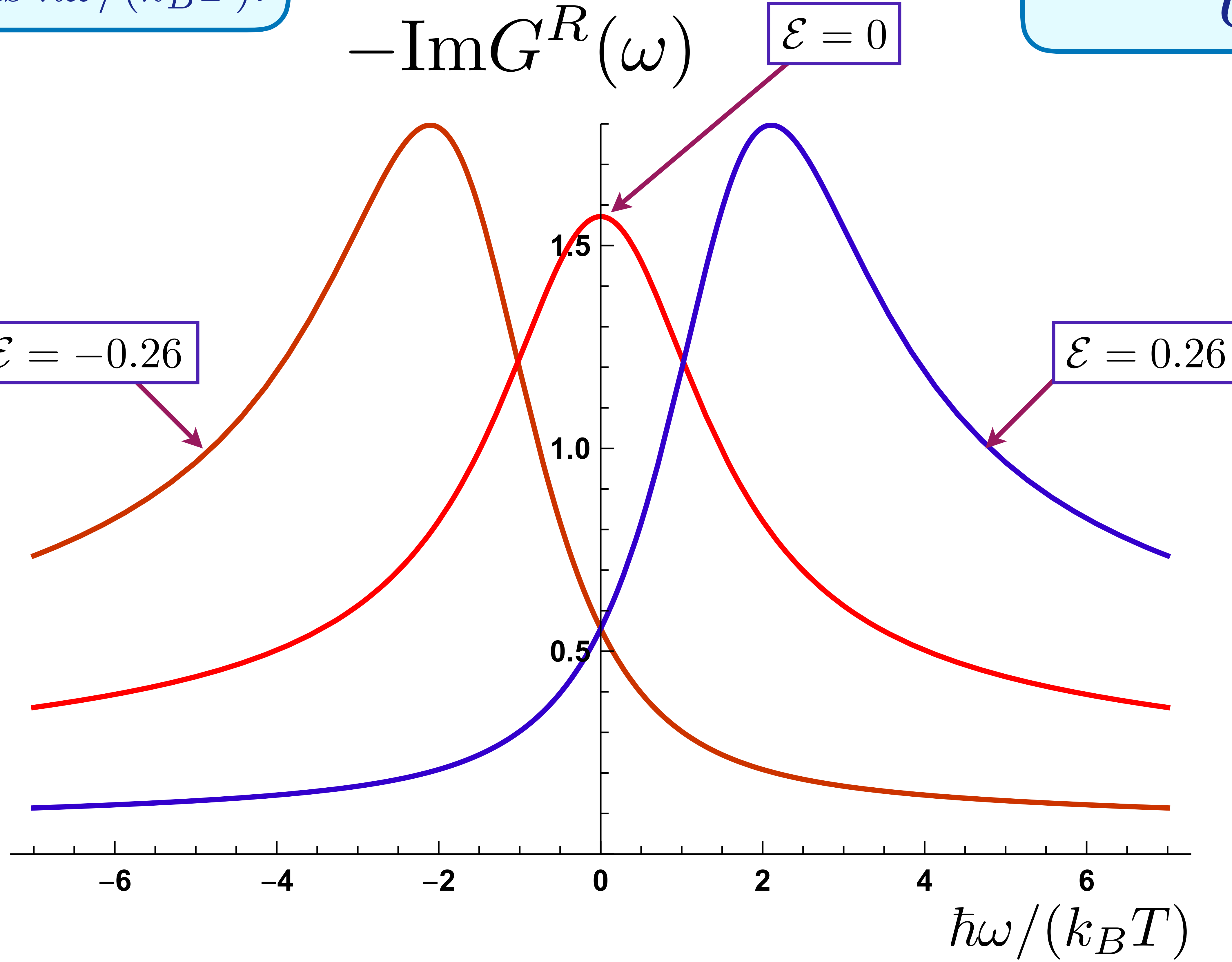
$$\mathcal{E} \propto \frac{e}{U}$$



The complex SYK model

ω dependence of G^R scales as $\hbar\omega/(k_B T)$.

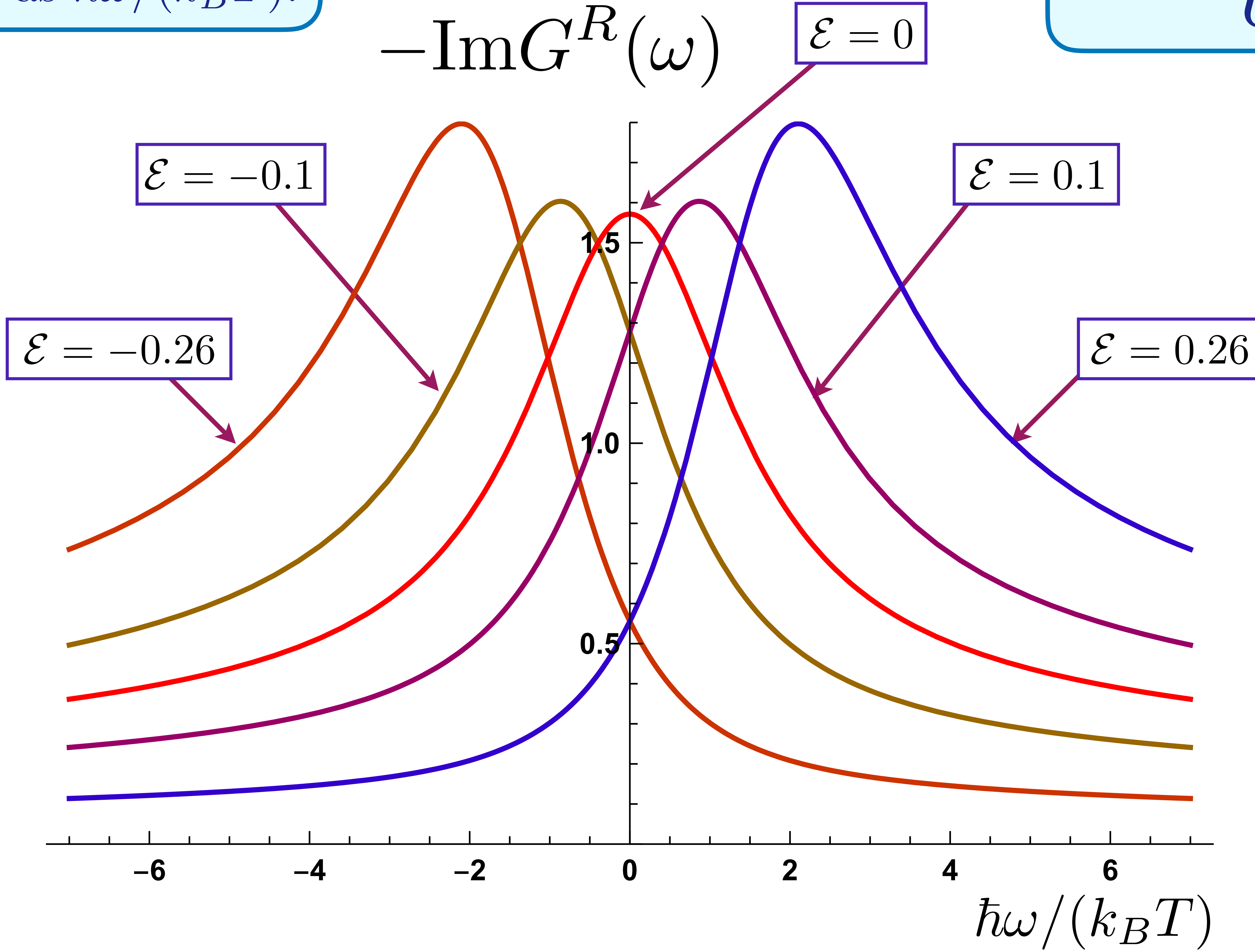
$$\mathcal{E} \propto \frac{e}{U}$$



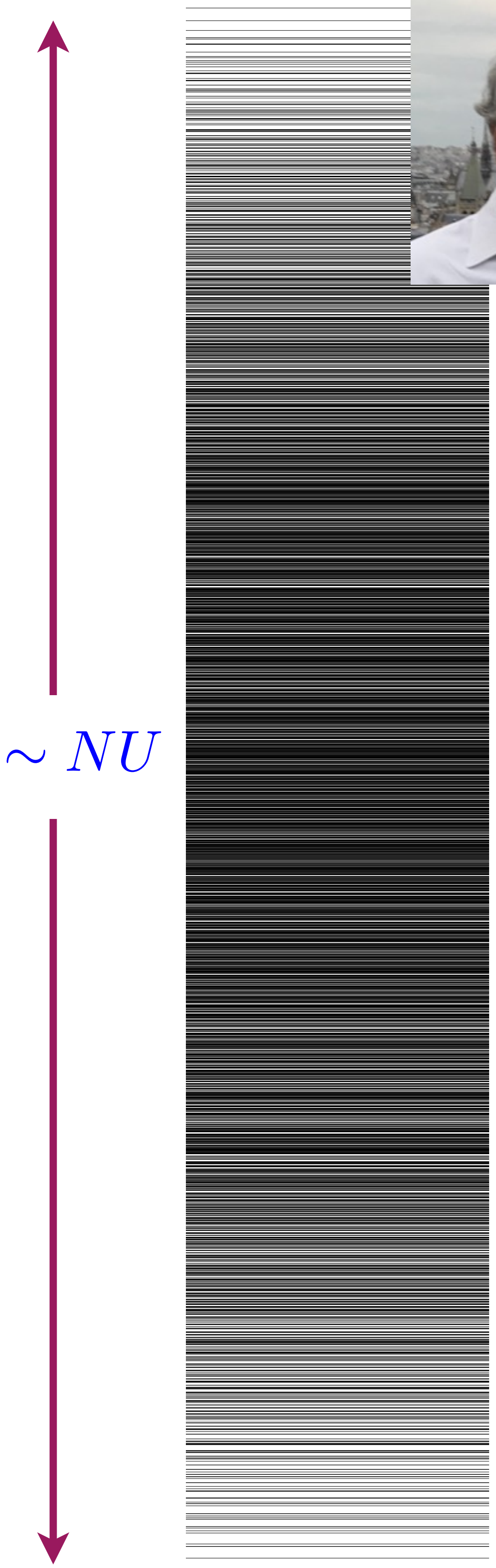
The complex SYK model

ω dependence of G^R scales as $\hbar\omega/(k_B T)$.

$$\mathcal{E} \propto \frac{e}{U}$$



The SYK model



GPS: A. Georges, O. Parcollet, and S. Sachdev, PRB **63**, 134406 (2001)

There are 2^N many body levels with energy E. Shown are all values of E for a single cluster of size $N = 12$. The $T \to 0$ state has an entropy $S_{GPS} = N s_0$, where $s_0 < \ln 2$ is determined by integrating

$$\frac{ds_0}{d\mathcal{Q}} = 2\pi\mathcal{E}\,.$$

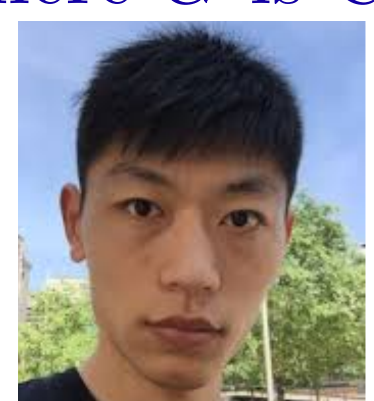
At $\mathcal{Q} = 1/2$,

$$s_0 = \frac{G}{\pi} + \frac{\ln(2)}{4} = 0.464848\ldots$$

where G is Catalan's constant.

Many-body level spacing $\sim 2^{-N} = e^{-N\ln 2}$

Non-quasiparticle excitations with spacing $\sim e^{-N s_0}$



W. Fu and S. Sachdev, PRB **94**, 035135 (2016)

A generalized SYK model

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} U_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell + e \sum_i c_i^\dagger c_i$$

$U_{ij;k\ell}$ are independent random variables

with $\overline{U_{ij;k\ell}} = 0$ and $\overline{|U_{ij;k\ell}|^2} = U^2$

A generalized SYK model

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta} \sum_{i,j,k,\ell=1}^{N} U_{ij\alpha\beta;k\ell\gamma\delta}\, c_{i\alpha}^\dagger c_{j\beta}^\dagger c_{k\gamma} c_{\ell\delta} + \sum_{i\alpha} e_\alpha c_{i\alpha}^\dagger c_{i\alpha}$$

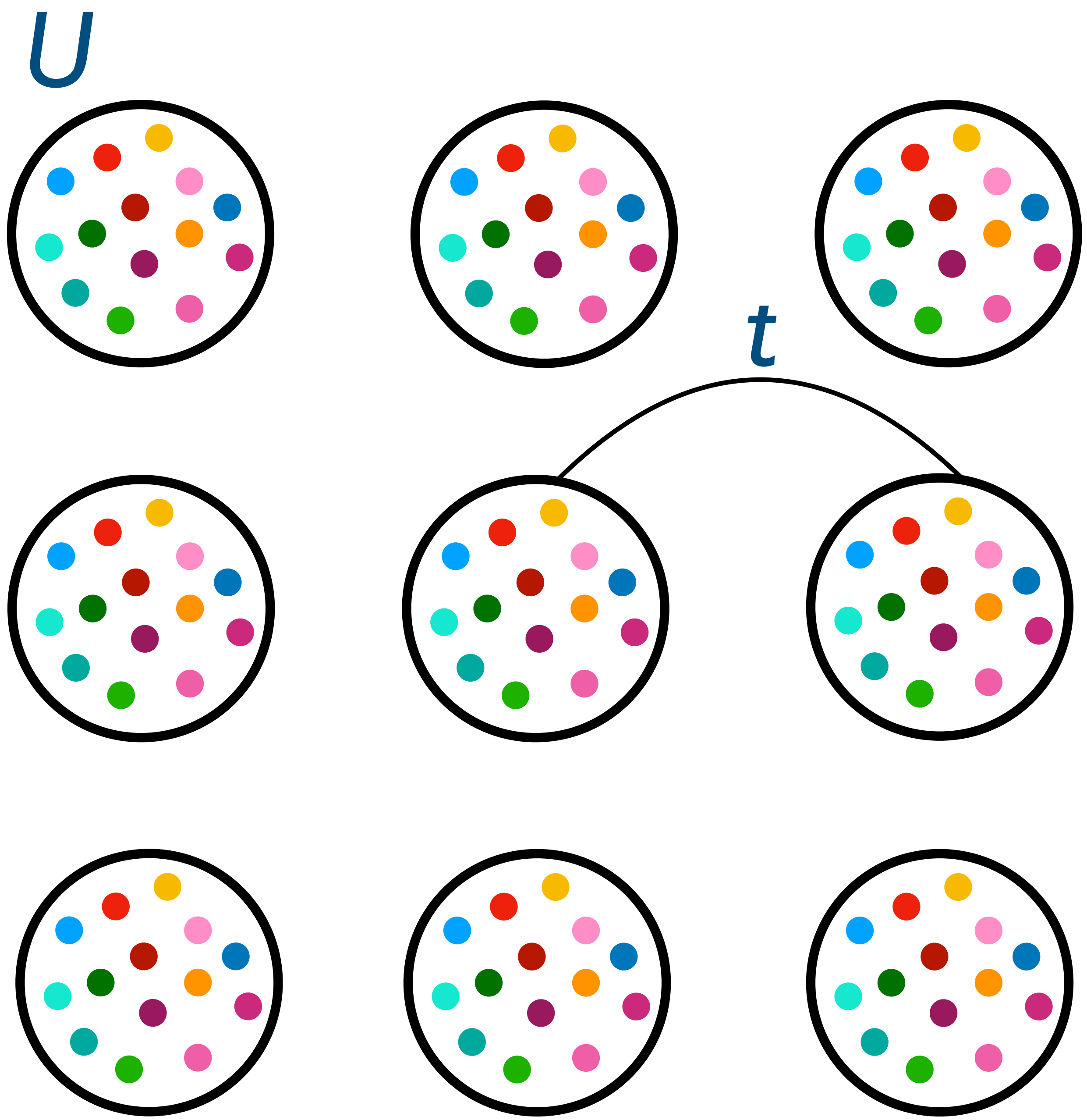
$U_{ij\alpha\beta;k\ell\gamma\delta}$ is a random function of $ijk\ell$ (as before)
e_α has a range of values of width W.

$\hbar\omega/(k_B T)$ scaling behavior of SYK holds for $W^2/U \ll k_B T \ll U$.

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)
Pengfei Zhang, PRB **96**, 205138 (2017)
Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, PRX **8**, 021049 (2018)
Aavishkar A. Patel, John McGreevy, Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)
See also Antoine Georges and Olivier Parcollet PRB **59**, 5341 (1999)

A generalized SYK model

$$H = \frac{1}{(2N)^{3/2}} \sum_x \sum_{i,j,k,\ell=1}^{N} U_{ij;k\ell} \, c_{ix}^\dagger c_{jx}^\dagger c_{kx} c_{\ell x} - t \sum_{\langle xx' \rangle} \sum_i c_{ix}^\dagger c_{ix'}$$



Translationally-invariant model with $\alpha\beta\gamma\delta \Rightarrow \mathbf{k}$ and $e_\alpha \Rightarrow e_\mathbf{k}$, yields 'incoherent metal' for $t^2/U \ll k_B T \ll U$ with $G(\mathbf{k}, \omega) = G_{\rm SYK}(\hbar\omega/(k_B T))$ independent of $\mathbf{k}$, and linear-in-T resistivity

$$\rho \sim \frac{h}{e^2} \frac{k_B T}{t^2/U}$$

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)
Pengfei Zhang, PRB **96**, 205138 (2017)
Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, PRX **8**, 021049 (2018)
Aavishkar A. Patel, John McGreevy, Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)
See also Antoine Georges and Olivier Parcollet PRB **59**, 5341 (1999)

A generalized SYK model

A. Patel and S. Sachdev, to appear

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta} \sum_{i,j,k,\ell=1}^{N} U_{ij\alpha\beta;k\ell\gamma\delta}\, c_{i\alpha}^\dagger c_{j\beta}^\dagger c_{k\gamma} c_{\ell\delta} + \sum_{i\alpha} e_\alpha c_{i\alpha}^\dagger c_{i\alpha}$$

$U_{ij\alpha\beta;k\ell\gamma\delta}$ is a random function of $ijk\ell$ (as before)

e_α has a range of values of width W.

$U_{ij\alpha\beta;k\ell\gamma\delta}$ is non-zero only for **resonant interactions**

with $e_\alpha + e_\beta = e_\gamma + e_\delta$.

A generalized SYK model

A. Patel and S. Sachdev, to appear

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta} \sum_{i,j,k,\ell=1}^{N} U_{ij\alpha\beta;k\ell\gamma\delta}\, c_{i\alpha}^\dagger c_{j\beta}^\dagger c_{k\gamma} c_{\ell\delta}$$

$$+ \sum_{i\alpha} e_\alpha c_{i\alpha}^\dagger c_{i\alpha}$$

$U_{ij\alpha\beta;k\ell\gamma\delta}$ is a random function of $ijk\ell$ (as before)

e_α has a range of values of width W.

$U_{ij\alpha\beta;k\ell\gamma\delta}$ is non-zero only for **resonant interactions**

with $e_\alpha + e_\beta = e_\gamma + e_\delta$.

SYK behavior in a '*Planckian metal*' as $T \to 0$,
with a remnant Fermi surface,
$G(\mathbf{k},\omega) = G_{\rm SYK}(\hbar\omega/(k_B T), \mathcal{E}_{\mathbf{k}})$, with $\mathcal{E}_{\mathbf{k}} \propto e_{\mathbf{k}}/U$,
and resistivity $\rho = \dfrac{m^*}{ne^2}\dfrac{1}{\tau}$,
with $\dfrac{1}{\tau} \approx \dfrac{k_B T}{\hbar}$ insensitive to U.

Ordinary metals:
quasiparticles

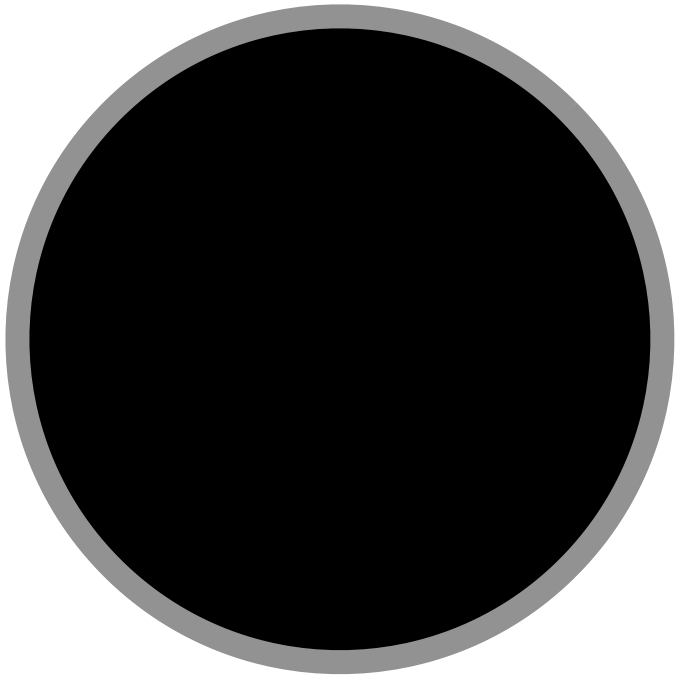
Strange metals:
no quasiparticles

Black
holes

Black Holes

Objects so dense that light is gravitationally bound to them.

In Einstein's theory, the region inside the black hole horizon is disconnected from the rest of the universe.



Quantum Black holes

- Black holes have an entropy and a temperature, T_H
- The entropy is proportional to their surface area.
- They relax to thermal equilibrium in a Planckian time $\sim \hbar/(k_B T_H)$.

J. D. Bekenstein, PRD **7**, 2333 (1973)
S.W. Hawking, Nature **248**, 30 (1974)

C. V. Vishveshwara, Nature **227**, 936 (1970)

Quantum Black holes

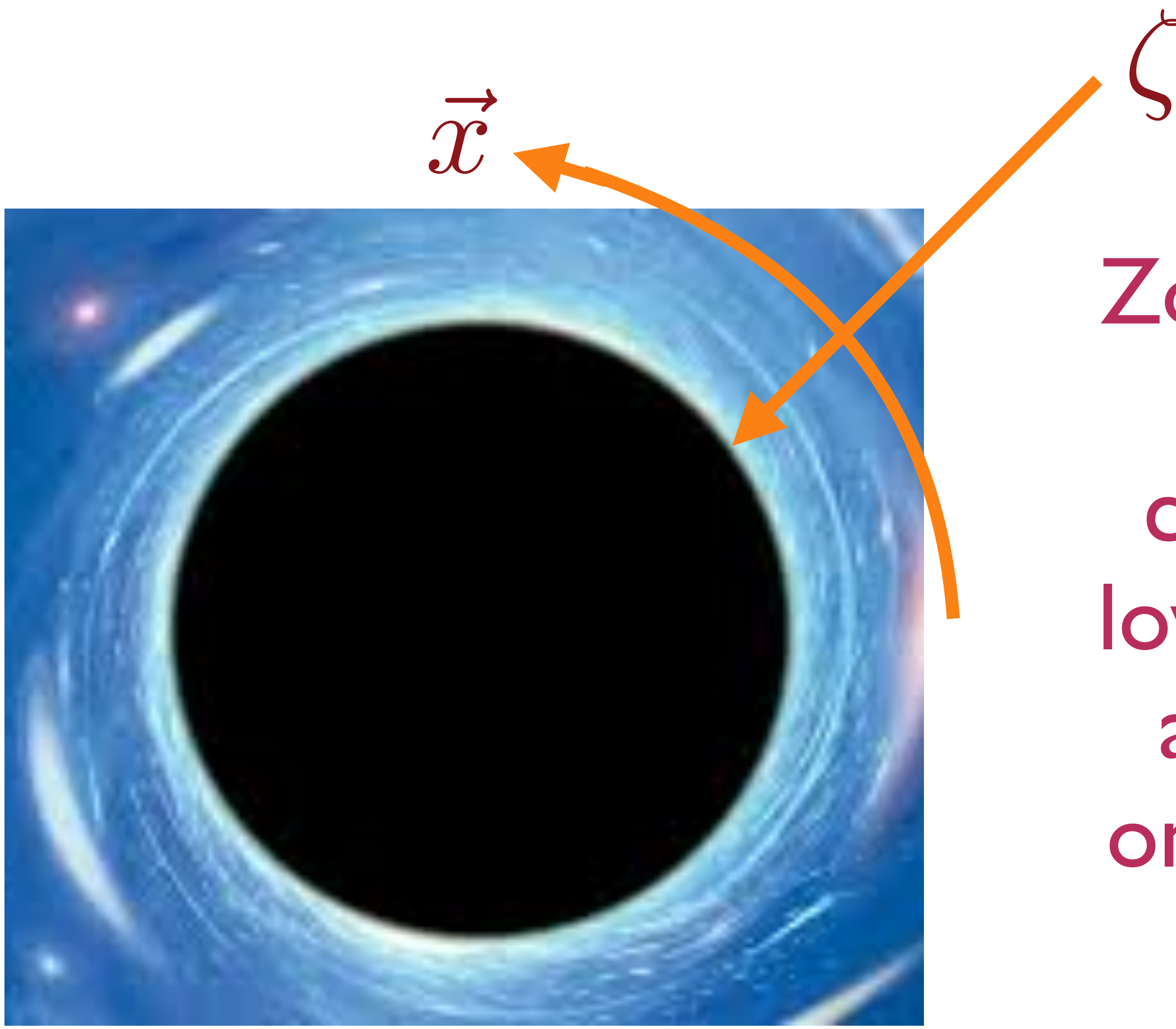
- Black holes have an entropy and a temperature, T_H
- The entropy is proportional to their surface area.
- They relax to thermal equilibrium in a Planckian time $\sim \hbar/(k_B T_H)$.

<u>Holography</u>:
Quantum black holes "look like" quantum many-particle systems without quasiparticle excitations, residing "on" the surface of the black hole

J. Maldacena, IJTP **38**, 1113 (1999); S.S. Gubser, I.R. Klebanov, and A.M. Polyakov Phys. Lett. B **428**, 105 (1998);
E. Witten, Adv. Theor. Math. Phys. **2**, 253 (1998)

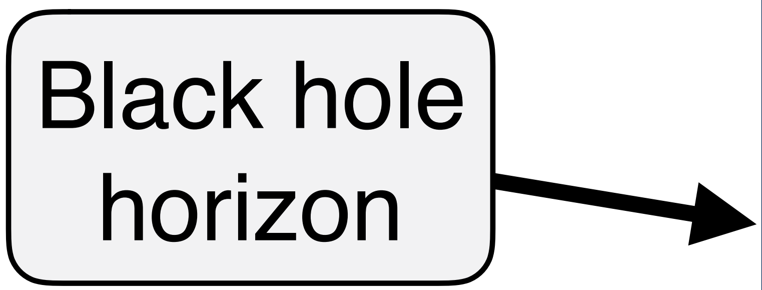
Work with a theory of Maxwell's electromagnetism and Einstein's general relativity. Include a negative cosmological constant, and examine black hole solutions with a net charge

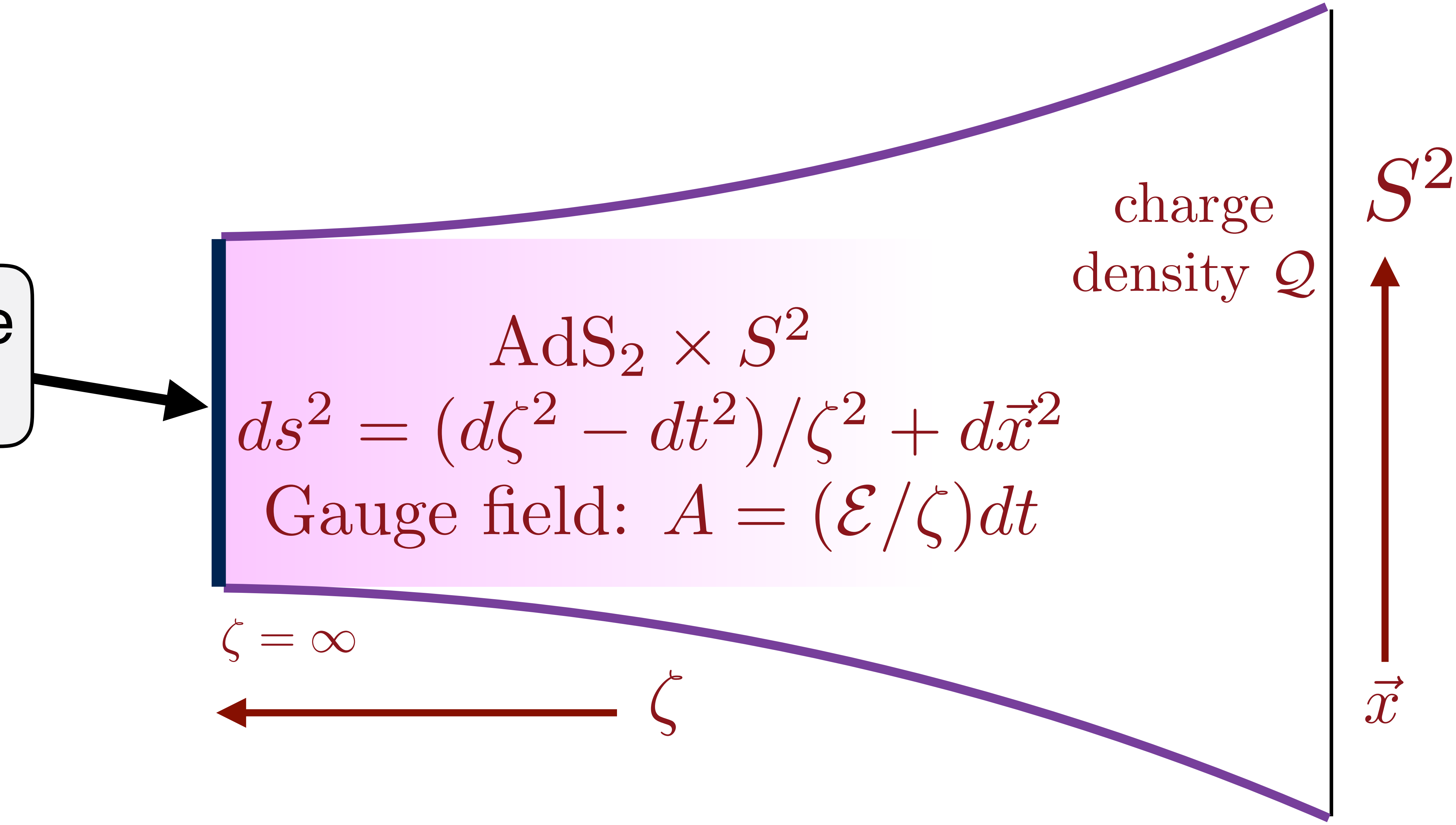
Work with a theory of Maxwell's electromagnetism and Einstein's general relativity. Include a negative cosmological constant, and examine black hole solutions with a net charge



Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension

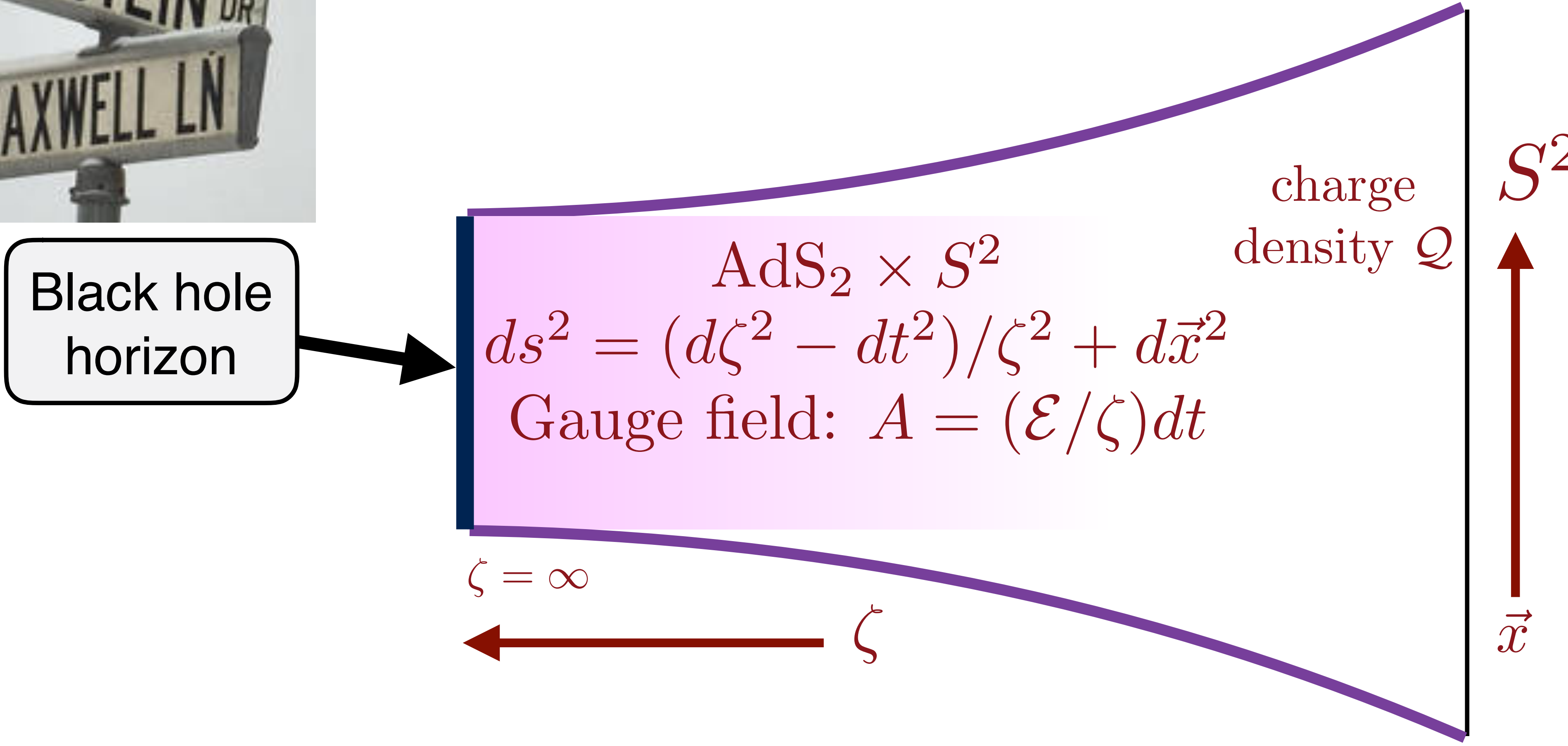
SYK model and charged black holes

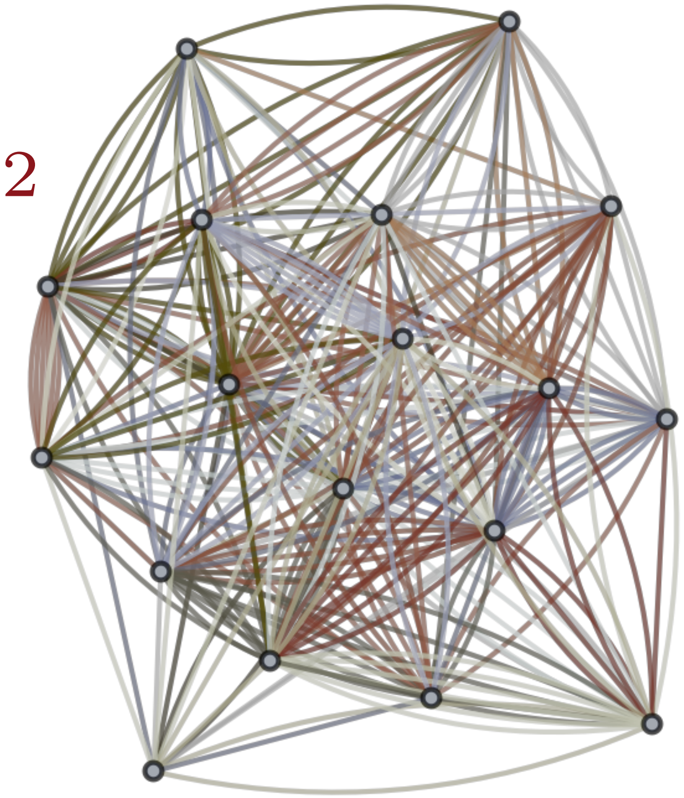




The near-horizon region of a charged black hole has the geometry of (1+1)-dimensional anti-de Sitter spacetime. By holography, this should map to a zero-dimensional quantum system: this turns out to be the SYK model

SYK model and charged black holes



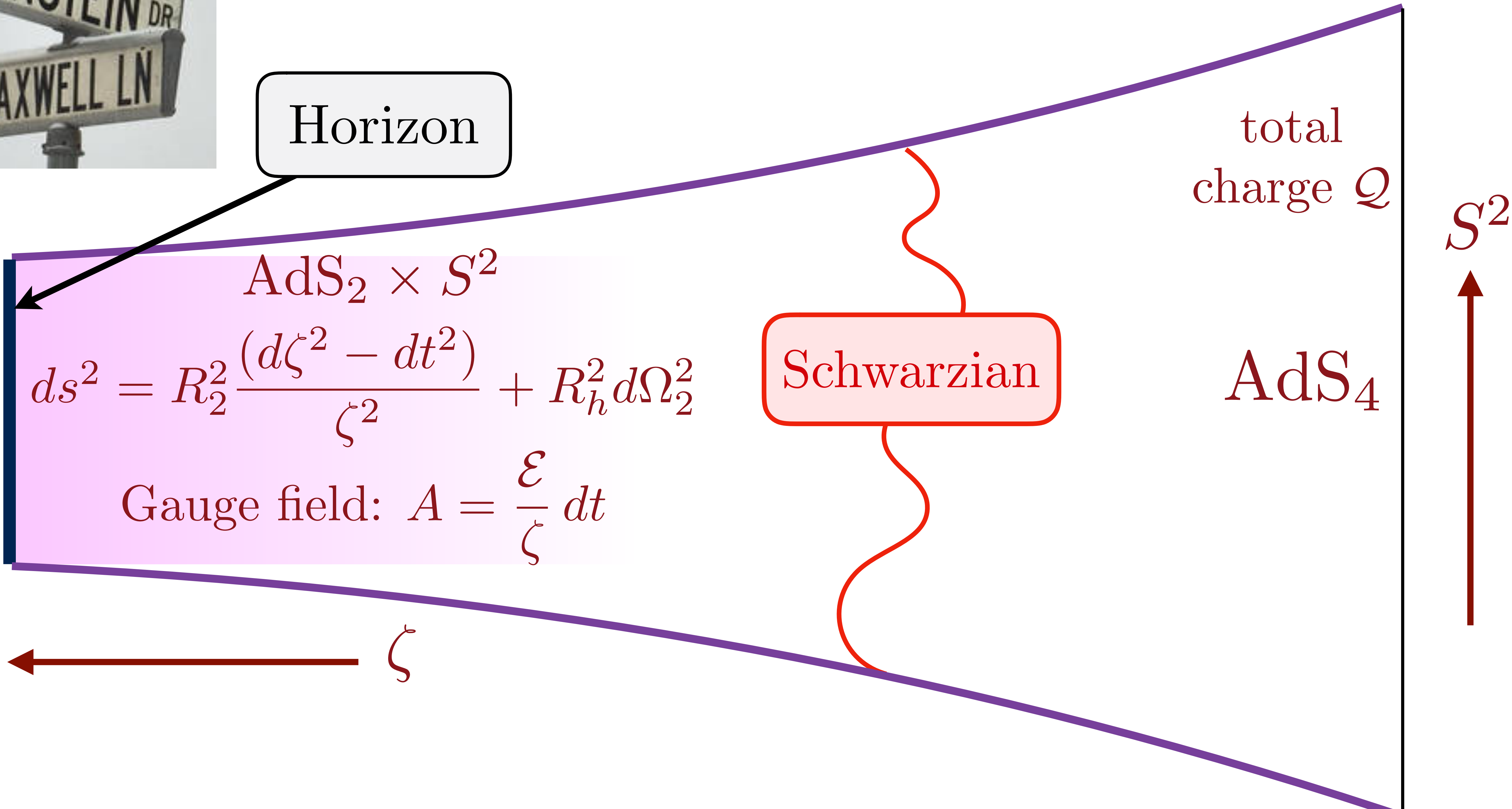


Bekenstein-Hawking entropy of AdS_2 horizon at $T = 0 \Leftrightarrow N s_0$ entropy of SYK model.

$\dfrac{\partial s_0}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$ holds for both the black hole and the SYK model, where $\mathcal{E}$ determines identical fermion spectral functions.

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010); PRX **5,** 041025 (2015)

SYK model and charged black holes



Remarkably, the correspondence between charged black holes and the SYK model also holds for the leading fluctuations at higher temperatures: both are described by a 'Schwarzian' theory with emergent SL(2,R) and U(1) gauge symmetries. For the black hole, the Schwarzian describes the fluctuations of the boundary between AdS_2 and AdS_4.

Main result

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010)

A. Kitaev (2015)

S. Sachdev, Phys. Rev. X **5**, 041025 (2015)

J. Maldacena and D. Stanford, Phys. Rev. D **94,** 106002 (2016)

J. Maldacena, D. Stanford, and Zhenbin Yang, PTEP 12C104 (2016)

K. Jensen, Phys. Rev. Lett. **117**, 111601 (2016)

J. Engelsoy, T.G. Mertens, and H. Verlinde, JHEP 1607 (2016) 139

R. Davison, Wenbo Fu, A. Georges, Yingfei Gu, K. Jensen, S. Sachdev,
Phys. Rev. B **95**, 155131 (2017)

A. Gaikwad, L.K. Joshi, G. Mandal, and S.R. Wadia, arXiv:1802.07746 P. Nayak, A. Shukla,

R.M. Soni, S.P. Trivedi, and V. Vishal, arXiv:1802.09547

P. Chaturvedi, Yingfei Gu, Wei Song, Boyang Yu, arXiv:1808.08062

U. Moitra, S. P. Trivedi, and V. Vishal, arXiv:1808.08239

S. Sachdev, arXiv:1902.04078

Main result

SYK model of fermions with random interactions of mean-square-value U, with total fermion number $\mathcal{Q}$, at temperatures $T \ll U$

Main result

SYK model of fermions with random interactions of mean-square-value U, with total fermion number $\mathcal{Q}$, at temperatures $T \ll U$

and

Charged black holes in 3+1 dimensions of radius R_h, with total charge $\mathcal{Q}$, at temperatures $T \ll 1/R_h$

are described by a common low energy quantum theory in $0+1$ dimensions

Main result

The common low T path integral is $\mathcal{Z} = \int \mathcal{D}f\, \mathcal{D}\phi\, e^{-I}$. This can be exactly evaluated, and the action is

$$I = -s_0 + \int_0^{1/T} d\tau \left\{ \frac{K}{2} \left(\frac{\partial \phi}{\partial \tau} + i(2\pi\mathcal{E}T)\frac{\partial f}{\partial \tau} \right)^2 - \frac{\gamma}{4\pi^2} \mathrm{Sch}[\tan(\pi T f(\tau)), \tau] \right\},$$

where $f(\tau)$ is a monotonic reparameterization of the temporal circle with

$f(\tau + 1/T) = f(\tau) + 1/T$,

ϕ is a phase conjugate to the charge density with

$\phi(\tau + 1/T) = \phi(\tau) + 2\pi n$, n integer,

$\mathrm{Sch}[g[\tau], \tau]$ is the Schwarzian derivative of $g(\tau)$.

The couplings are related to the entropy $S(T, \mathcal{Q})$ and the chemical potential μ via

$$S(T \to 0, \mathcal{Q}) = s_0 + \gamma T, \quad K = \left(\frac{d\mathcal{Q}}{d\mu} \right)_{T \to 0}, \quad 2\pi\mathcal{E} = \frac{ds_0}{d\mathcal{Q}}$$

Main result

- Closely related to, but not the usual AdS/CFT correspondence, which involves only neutral black holes at $T > 0$.

- Unlike the AdS/CFT correspondence, *both* sides of the duality are fully solvable. This has enabled numerous recent studies of black holes quantum information.

Quantum matter without quasiparticles

- Planckian dynamics (*i.e.* fastest possible local thermalization in a time $\hbar/(k_B T)$) is realized in the 'solvable' SYK models.

Quantum matter without quasiparticles

- Planckian dynamics (*i.e.* fastest possible local thermalization in a time $\hbar/(k_B T)$) is realized in the 'solvable' SYK models.

- Momentum space SYK model yields Planckian transport with resistivity $\rho \approx (m^*/(ne^2))(k_B T/\hbar)$.

Quantum matter without quasiparticles

- Planckian dynamics (*i.e.* fastest possible local thermalization in a time $\hbar/(k_B T)$) is realized in the 'solvable' SYK models.

- Momentum space SYK model yields Planckian transport with resistivity $\rho \approx (m^*/(ne^2))(k_B T/\hbar)$.

- Black holes thermalize in a Planckian time $\sim \hbar/(k_B T_H)$, where T_H is the Hawking temperature.

Quantum matter without quasiparticles

- Planckian dynamics (*i.e.* fastest possible local thermalization in a time $\hbar/(k_B T)$) is realized in the 'solvable' SYK models.

- Momentum space SYK model yields Planckian transport with resistivity $\rho \approx (m^*/(ne^2))(k_B T/\hbar)$.

- Black holes thermalize in a Planckian time $\sim \hbar/(k_B T_H)$, where T_H is the Hawking temperature.

- A Schwarzian theory of a time reparameterization mode, with SL(2,R) symmetry, (along with a phase fluctuating mode) describes the quantum dynamics of
  - the SYK models
  - black holes with near-extremal AdS_2 horizons

Thanks to my family !

Menaka Sachdev

Usha Pasi

Monisha Sachdev