Planckian metals and black holes

1st International Symposium
on Trans Scale Quantum Science,
Trans-Scale Quantum Science Institute,
University of Tokyo, October 28, 2021

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

1. Introduction to Planckian metals

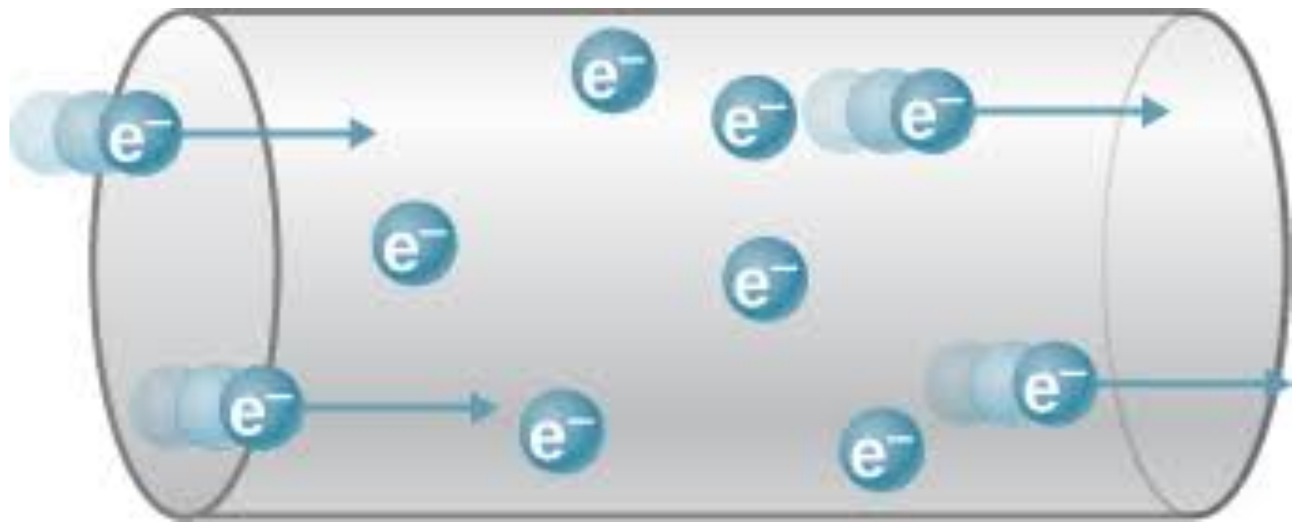
2. Introduction to black holes

3. The SYK model

4. Progress on the theory of black holes

5. Progress on the theory of Planckian metals

Current flow with quasiparticles in Copper

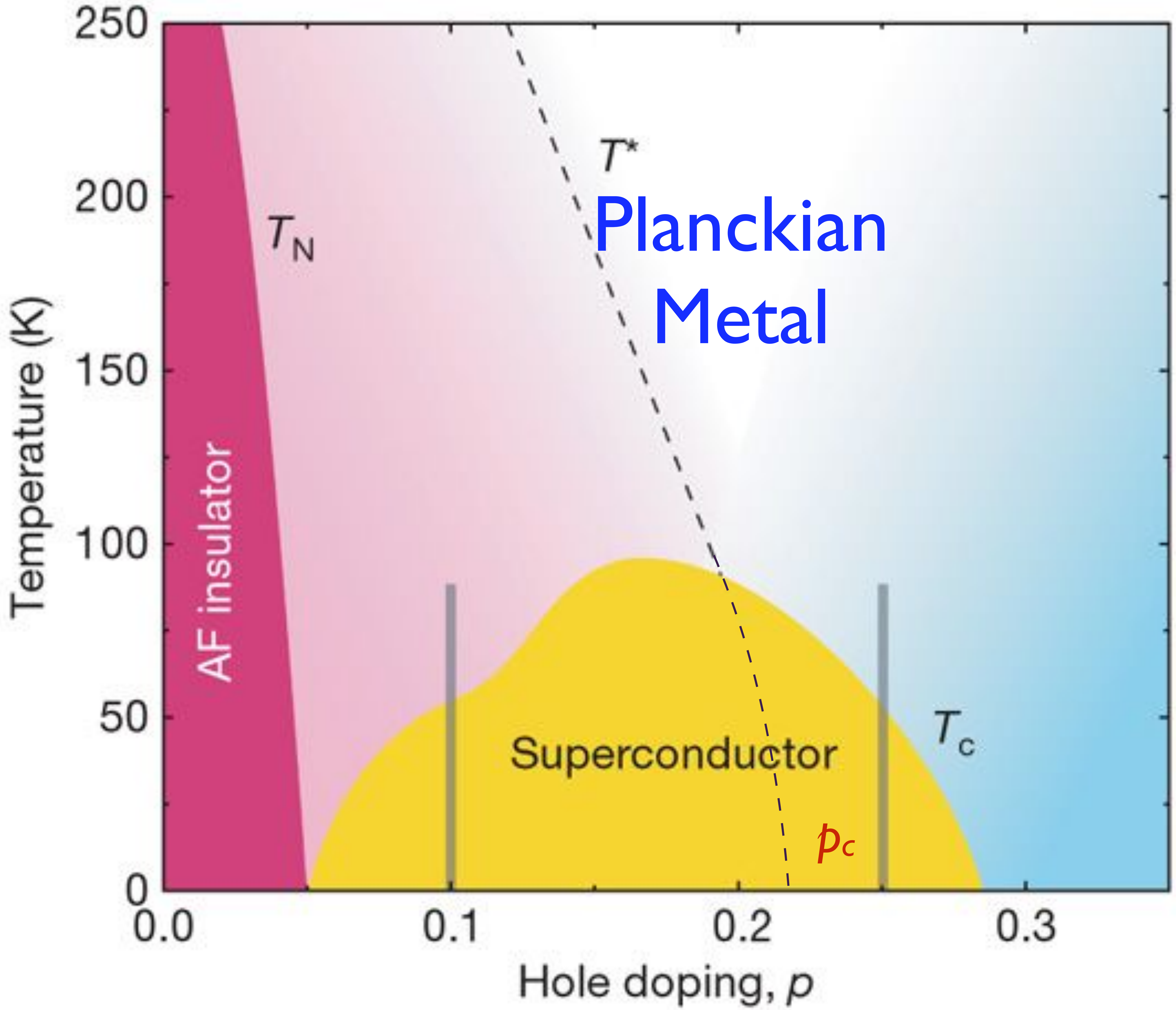


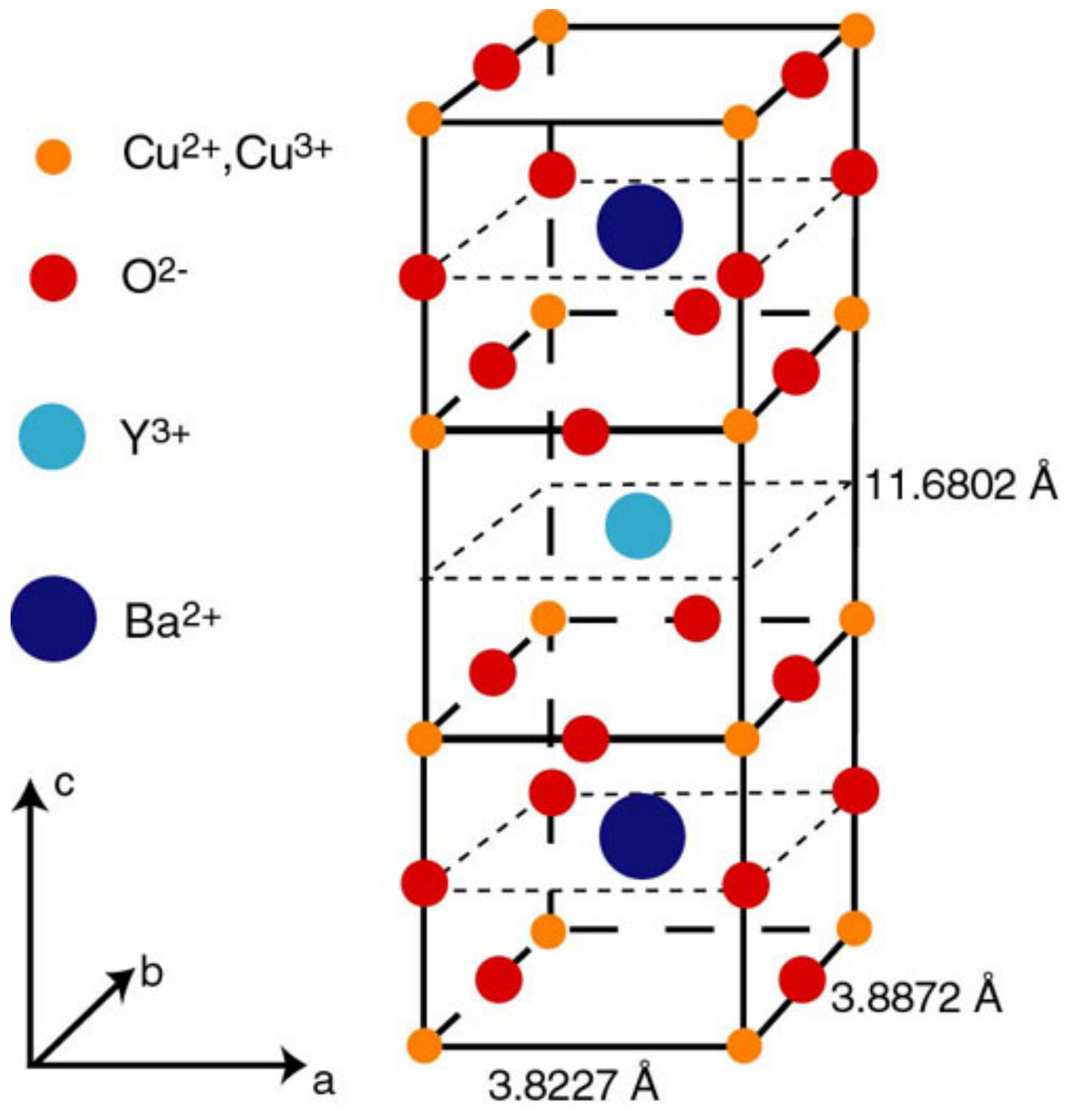
Flowing quasiparticles scatter off each other in a typical scattering time τ

This time is much longer than a limiting 'Planckian time' $\dfrac{\hbar}{k_B T}$.

The long scattering time implies that quasiparticles are well-defined.

The motion of quasiparticles is 'ballistic' or 'integrable'
up to the long time τ, after which it is chaotic.

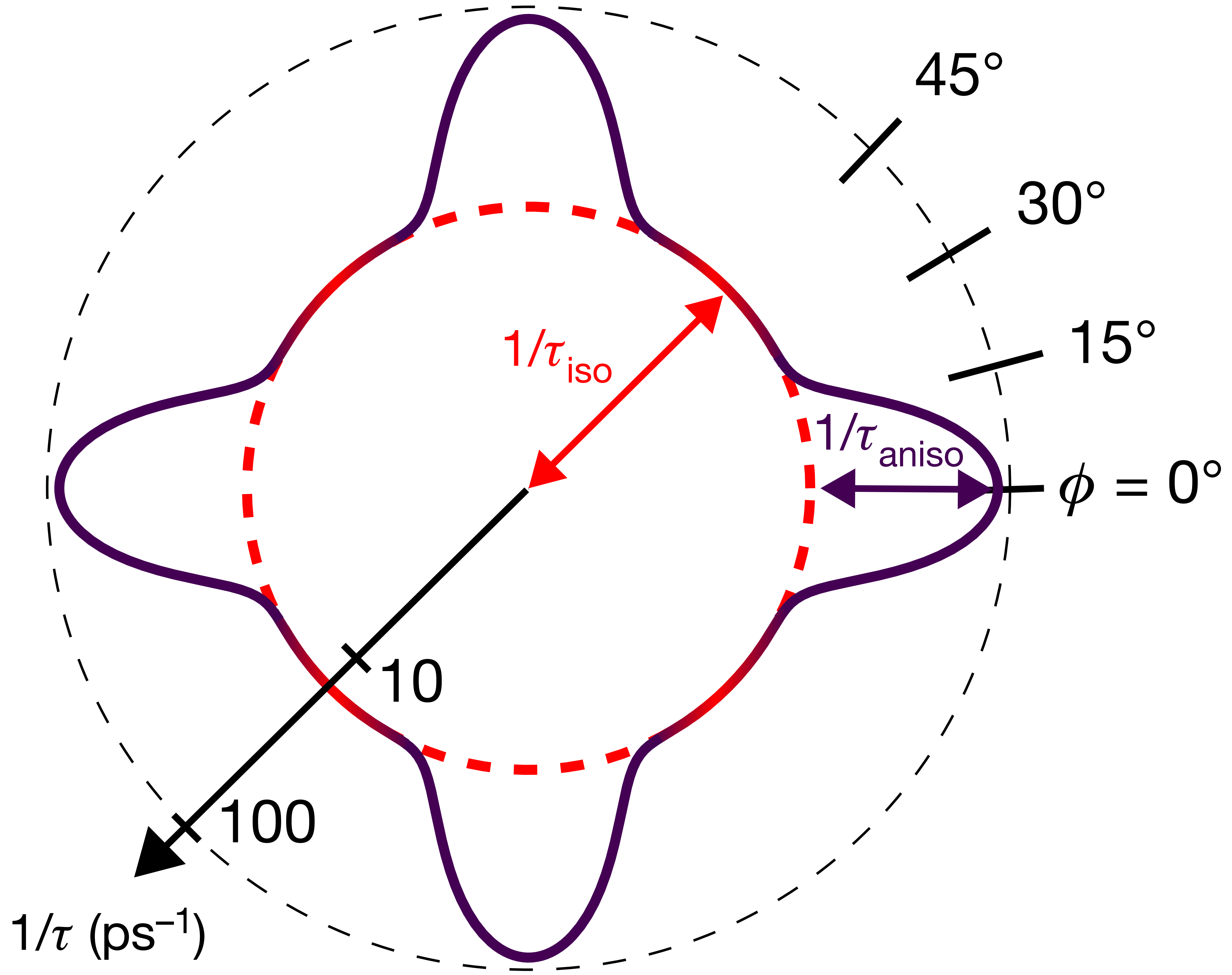

250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Planckian
Metal
Superconductor
T_c
p_c

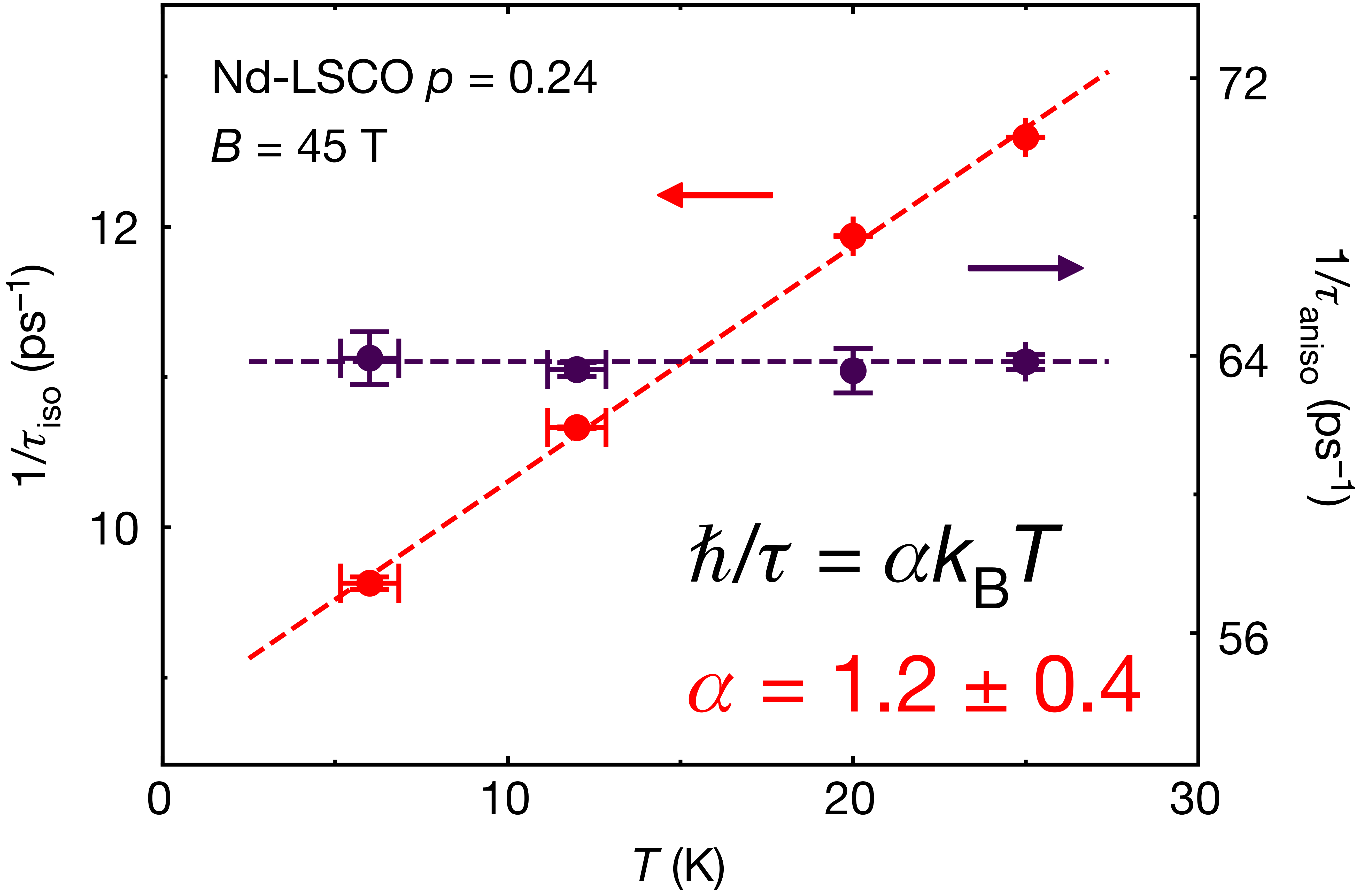

Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

Linear-in temperature resistivity from an isotropic Planckian scattering rate

Nature **595**, 667-672 (2021)

G. Grissonnanche, Y. Fang, A. Legros, S. Verret, F. Laliberté, C. Collignon, J. Zhou, D. Graf, P. Goddard, L. Taillefer, B. J. Ramshaw





Questions

- Theory for a fermion system with variable density without quasiparticles, and relaxation time $\sim \hbar/(k_B T)$.
- Needed: theory for collision time in resistivity $\sim \hbar/(k_B T)$.
- Needed: theory for the appearance of superconductivity (and other broken symmetries) in such a 'Planckian metal'.

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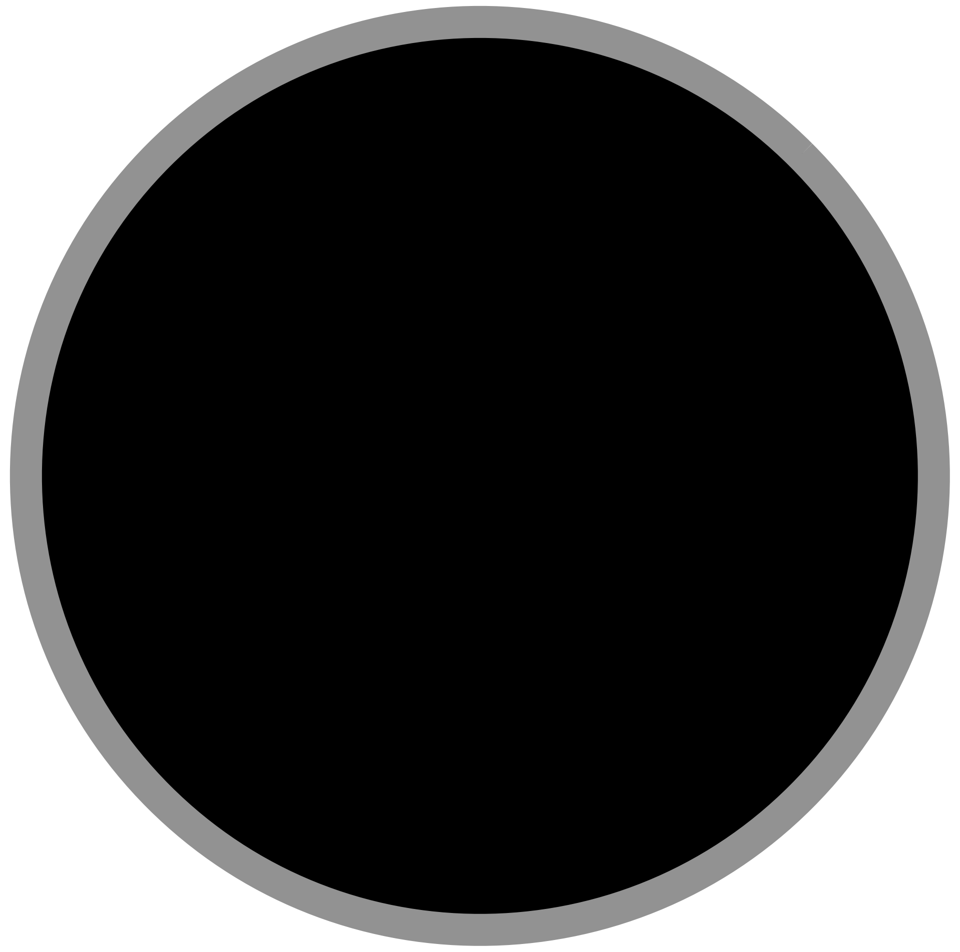
Black Holes

Objects so dense that light is gravitationally bound to them.

Horizon radius $R = \dfrac{2GM}{c^2}$

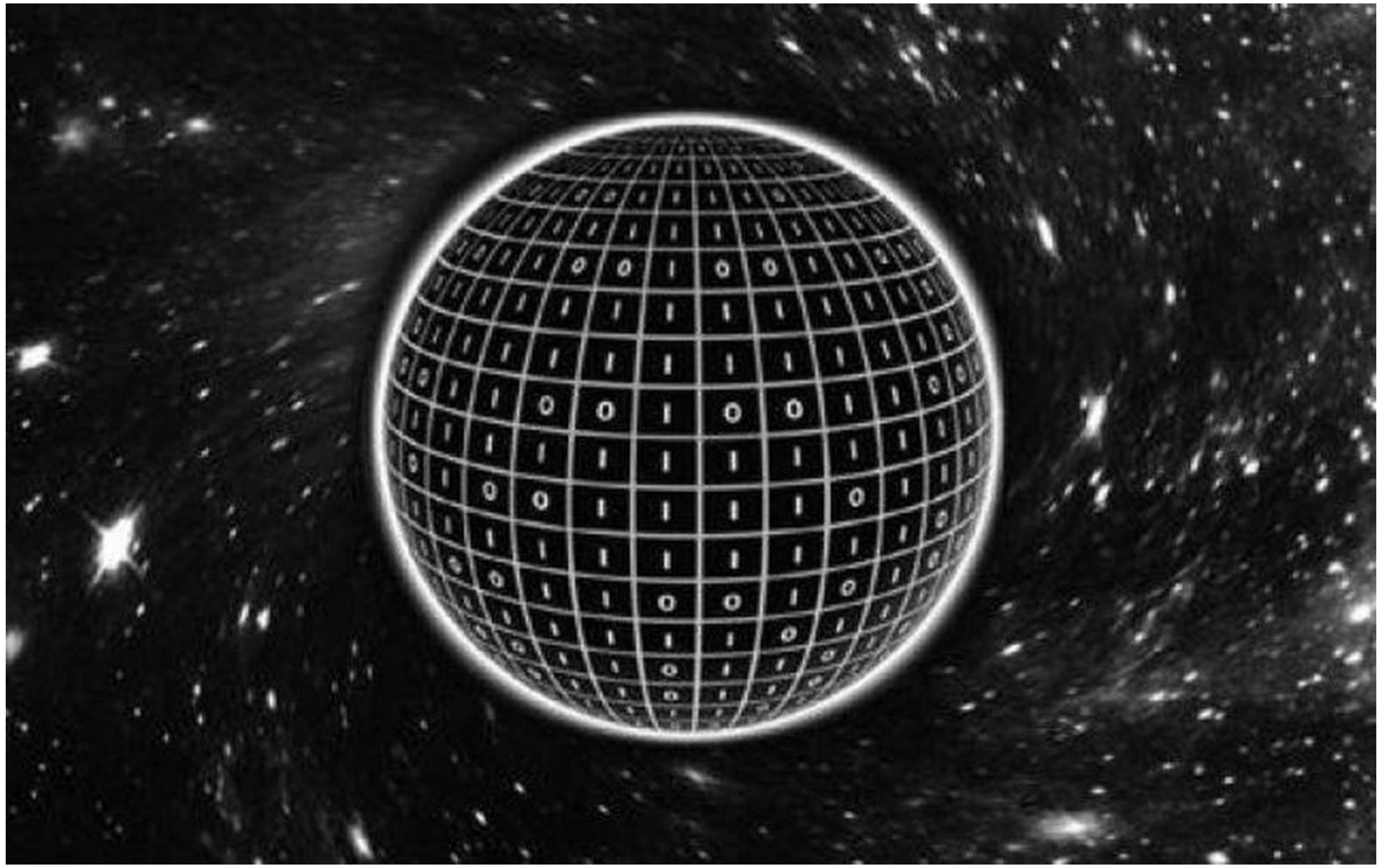


G Newton's constant, c velocity of light, M mass of black hole

For $M =$ earth's mass, $R \approx 9\,mm$!

Quantum Black holes

- Black holes have an entropy and a temperature, $T_H = \hbar c^3/(8\pi G M k_B)$.
- The entropy is proportional to their surface area.



T.B. BAKKER / DR. J.P. VAN DER SCHAAR

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

Remarkable features:

- Entropy is finite.
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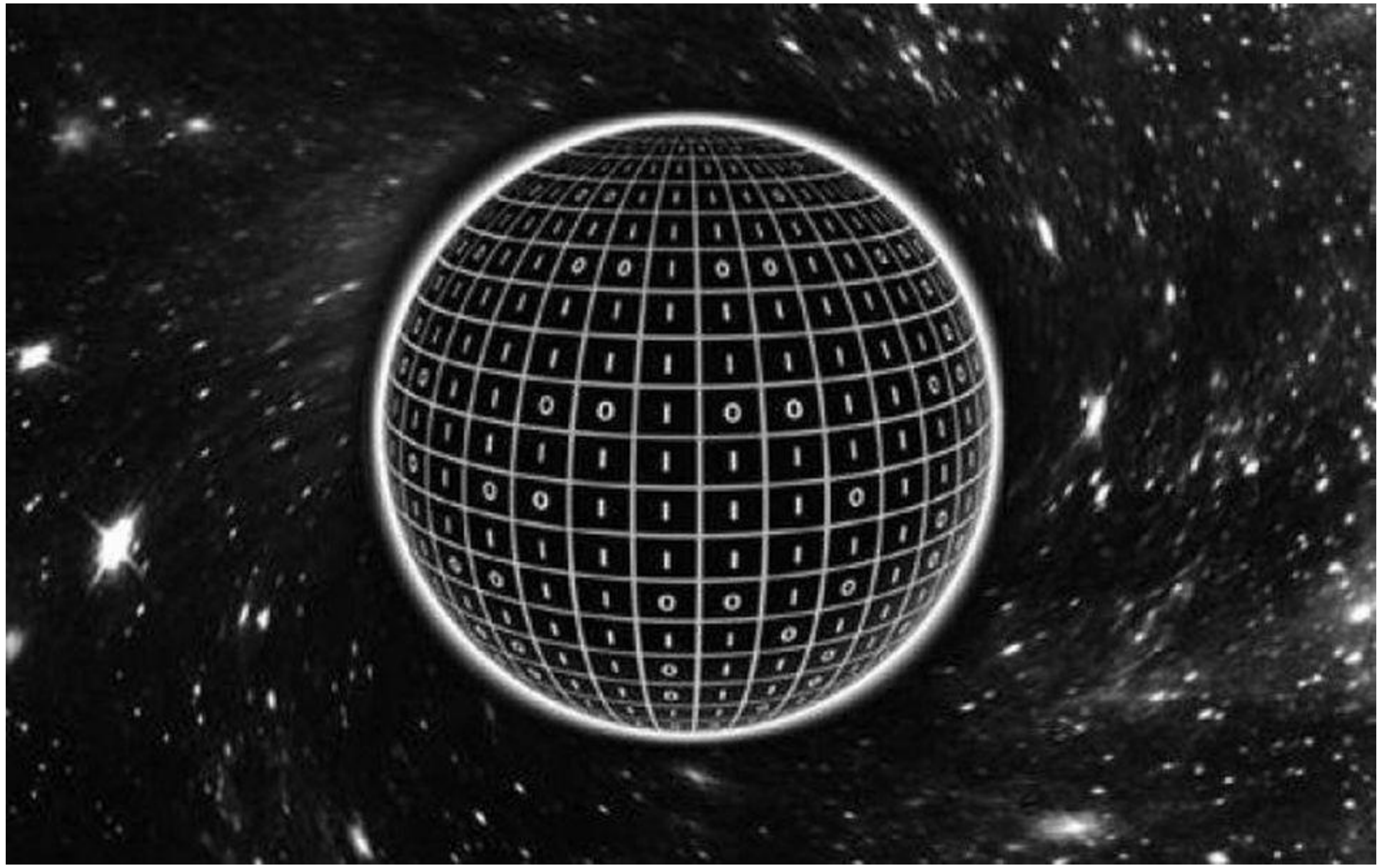

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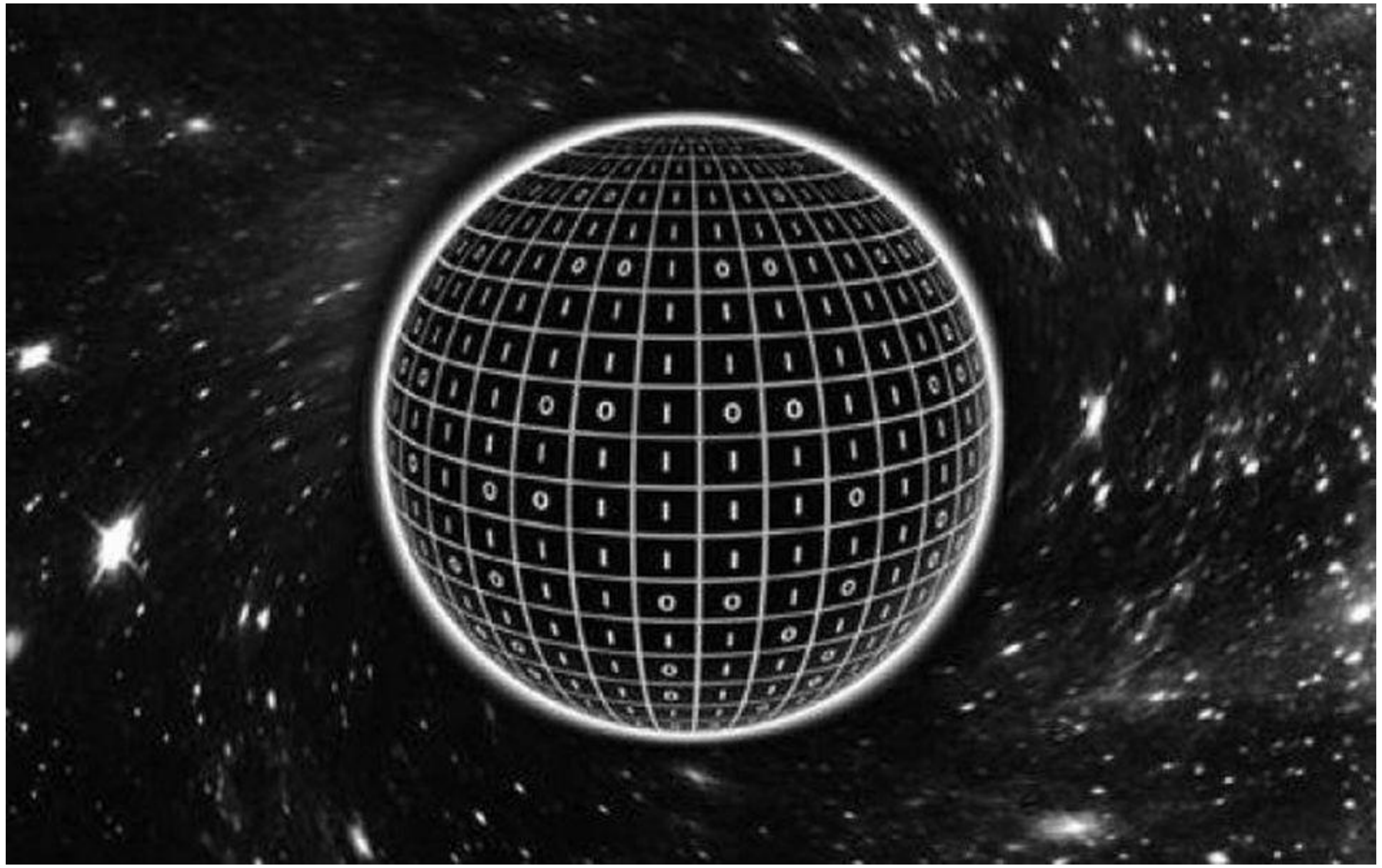

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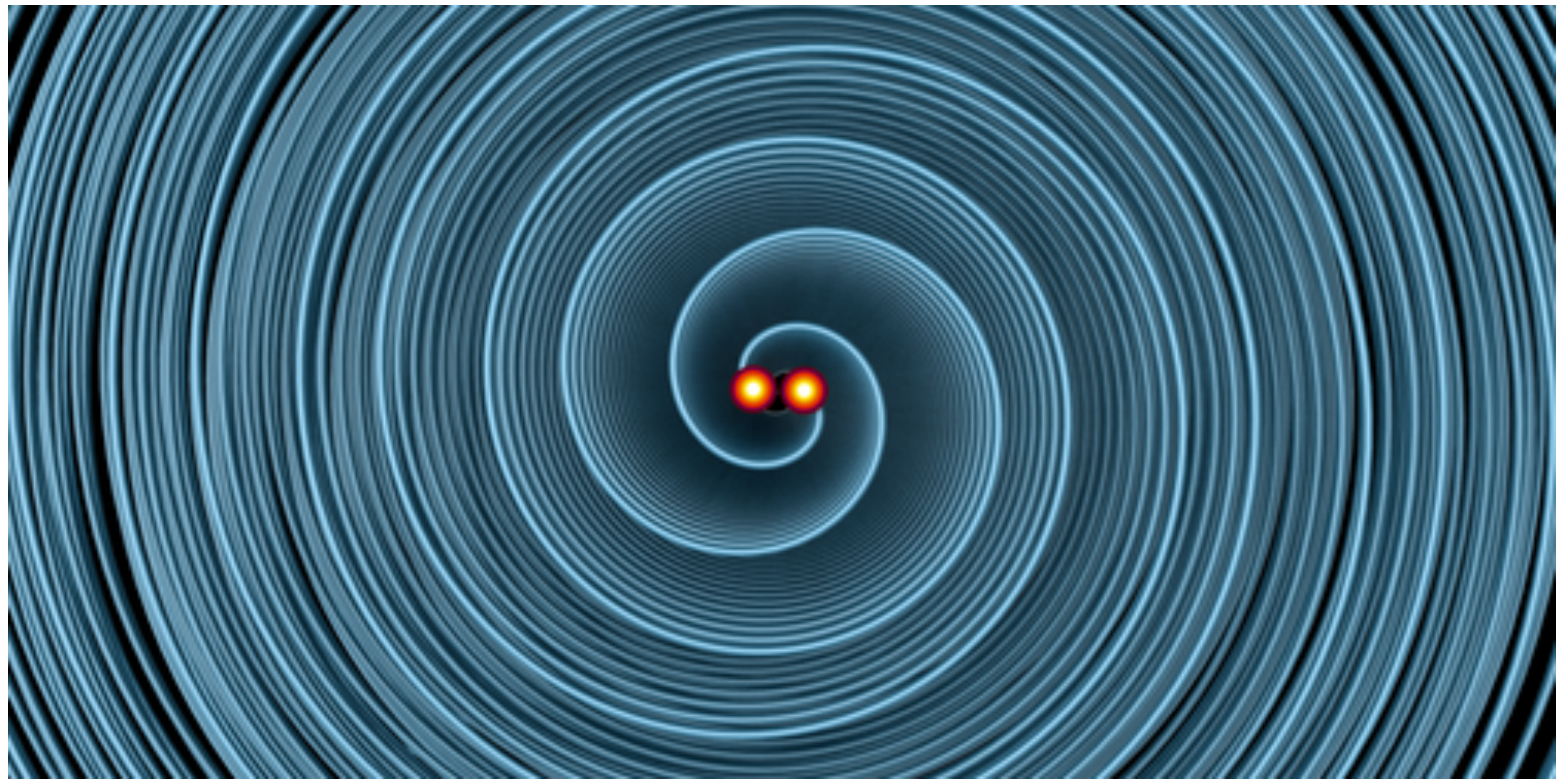
Black Holes Obey Information-Emission Limits

April 22, 2021 • *Physics* 14, s47 –Christopher Crockett

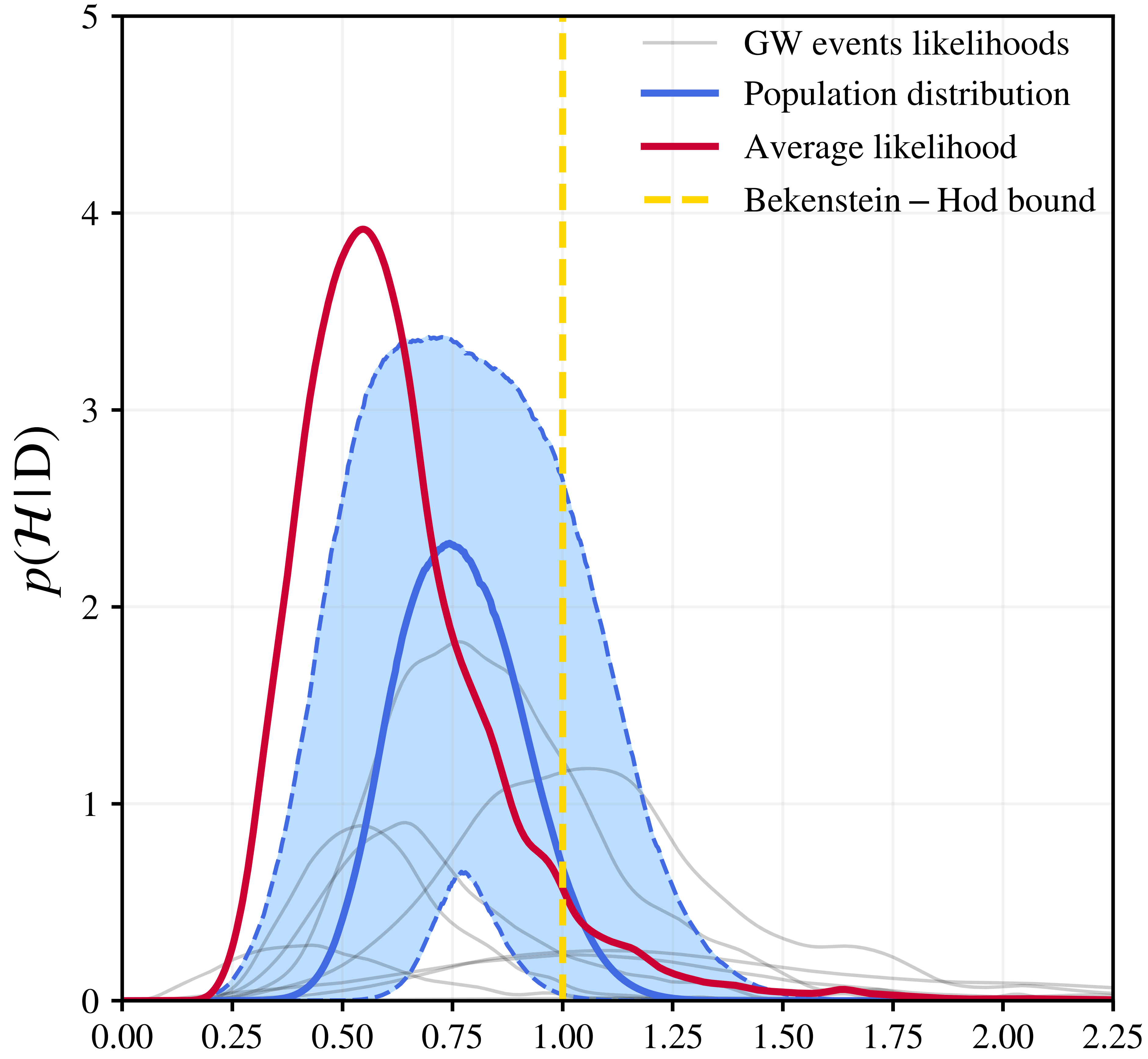
G. Carullo, D. Laghi, J. Veitch, W. Del Pozzo, Phys. Rev. Lett. **126**, 161102 (2021)

An analysis of the gravitational waves emitted from black hole mergers confirms that black holes are the fastest known information dissipaters.



Gravity wave observations of 8 different black holes show a relaxation time

$$\tau \sim \frac{\hbar}{k_B T}$$



$$\mathcal{H} = \frac{1}{\pi} \frac{\hbar/\tau}{k_B T}$$

Thermodynamics of quantum black holes with charge Q:

$$\int \mathcal{D}g_{\mu\nu}\mathcal{D}A_\mu \exp\left(-\frac{1}{\hbar}\,\mathcal{S}^{(3+1)}_{\text{Einstein gravity+Maxwell EM}}[g_{\mu\nu}, A_\mu]\right)$$

Metric of spacetime

Electromagnetic gauge field

In general, this integral is not well defined, because of an uncontrollably large number of spacetime configurations.

Thermodynamics of quantum black holes with charge $\mathcal{Q}$:

$$\int \mathcal{D}g_{\mu\nu}\mathcal{D}A_\mu \exp\left(-\frac{1}{\hbar}\,\mathcal{S}^{(3+1)}_{\text{Einstein gravity+Maxwell EM}}[g_{\mu\nu}, A_\mu]\right)$$

$$= \exp\Big(S_{BH}\Big) \times \Bigg(\quad ....????... \quad \Bigg)$$

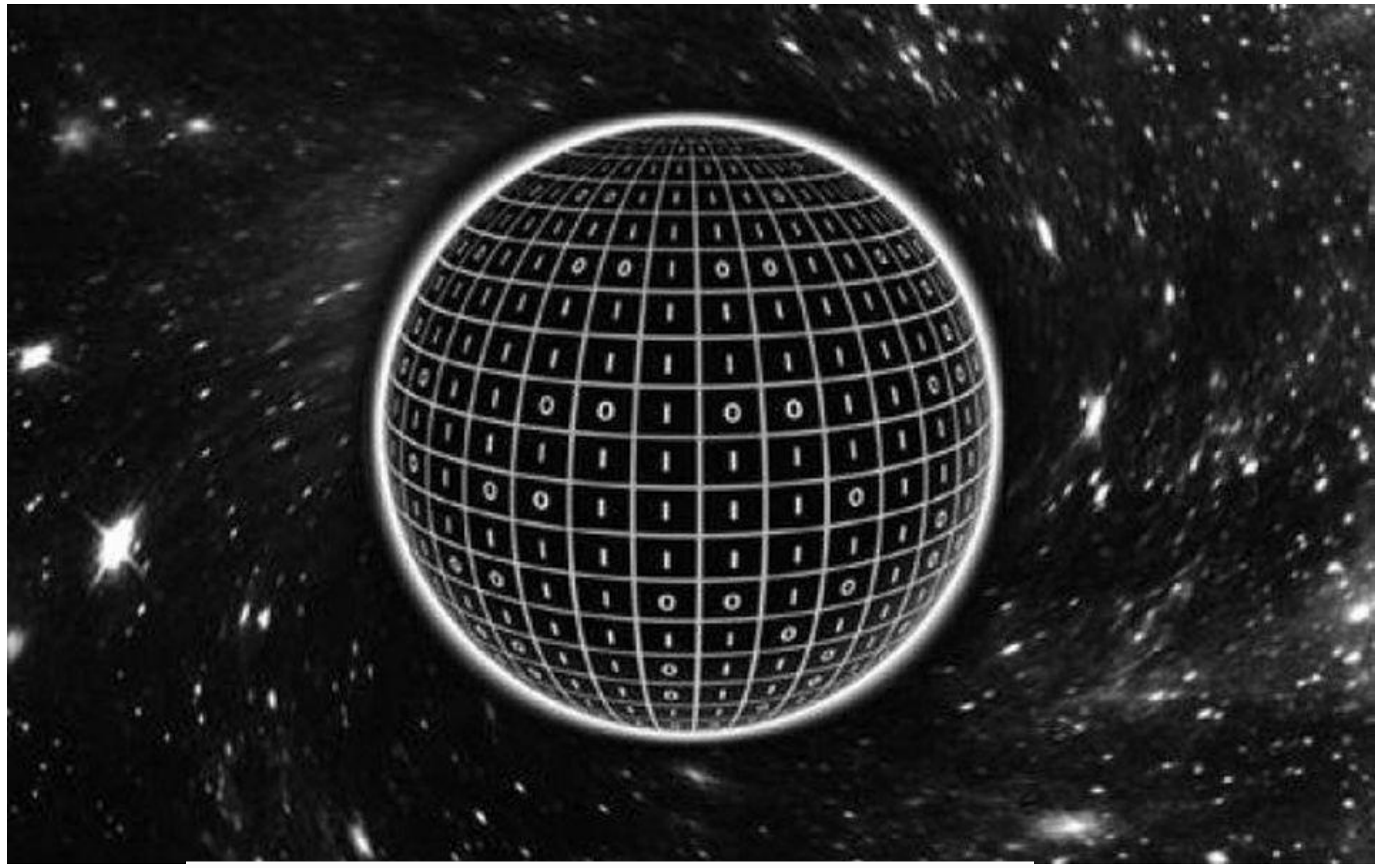
Gibbons, Hawking (1977)
Chambin, Emparan, Johnson, Myers (1999)

$$S_{BH}(T \to 0, \mathcal{Q}) = \frac{A(T)c^3}{4G\hbar} = \frac{A_0 c^3}{4G\hbar}\left(1 + \frac{2(\pi A_0)^{1/2}T}{\hbar c}\right)$$

A_0 is the area of the charged black hole horizon at $T = 0$.
$\mathcal{Q}$ is the black hole charge.
A_0 is a function of $\mathcal{Q}$.

Questions

- Is Einstein-Maxwell theory meaningful beyond the saddle point, and can we compute quantum fluctuation corrections to S_{BH}?
- Can the resulting entropy be understood as that of a unitary quantum system with a discrete spectrum ?
- Can we compute the evolution of the entropy as the black hole evaporates? Is it that of an evaporating unitary quantum system?



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A simple model of a metal with quasiparticles

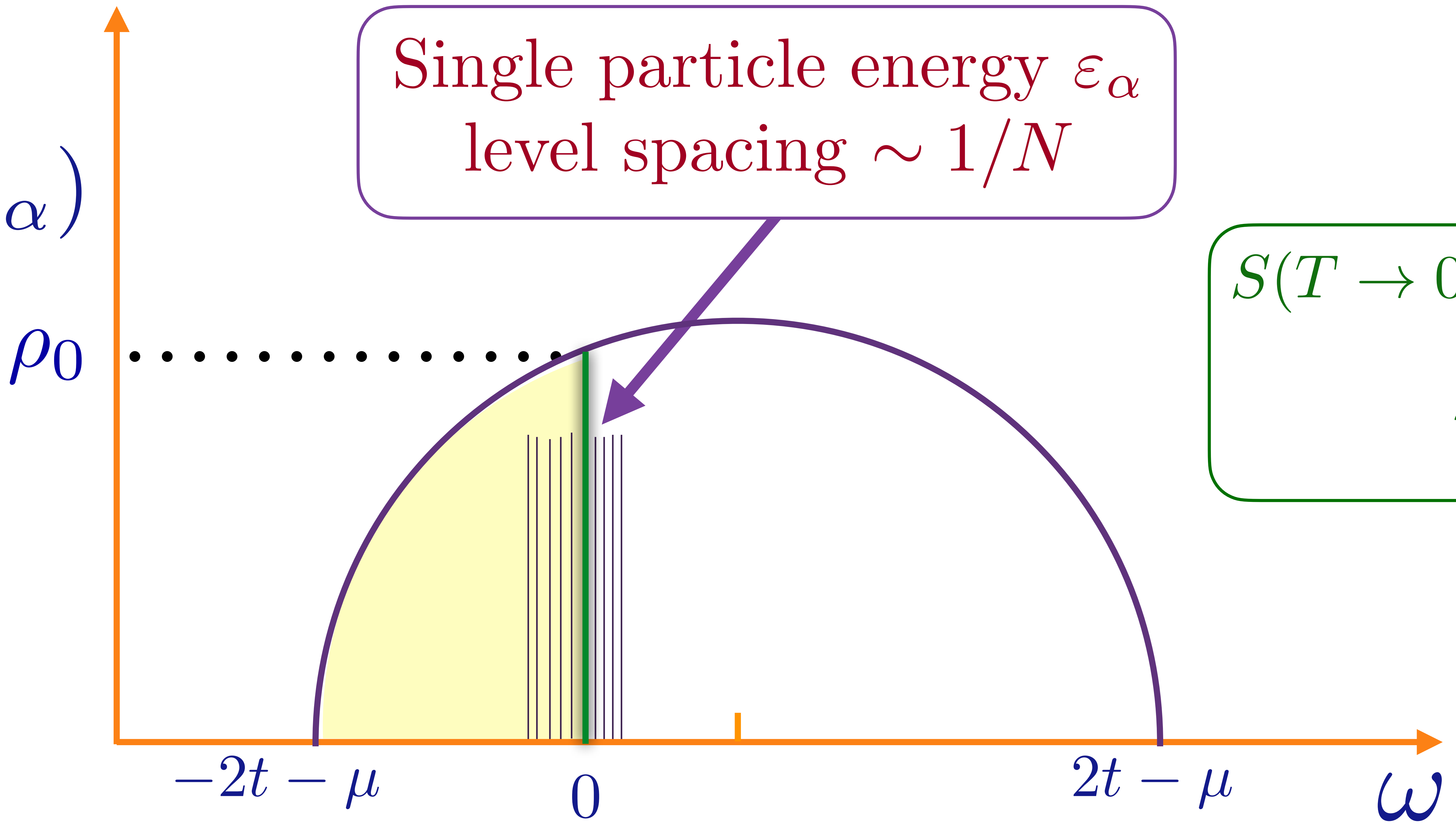
$$H = \frac{1}{(N)^{1/2}} \sum_{i,j=1}^{N} t_{ij} c_i^\dagger c_j - \mu \sum_i c_i^\dagger c_i$$

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

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

t_{ij} are independent random variables with $\overline{t_{ij}} = 0$ and $\overline{|t_{ij}|^2} = t^2$

$$\rho(\omega) = \frac{1}{N} \sum_\alpha \delta(\omega - \varepsilon_\alpha)$$

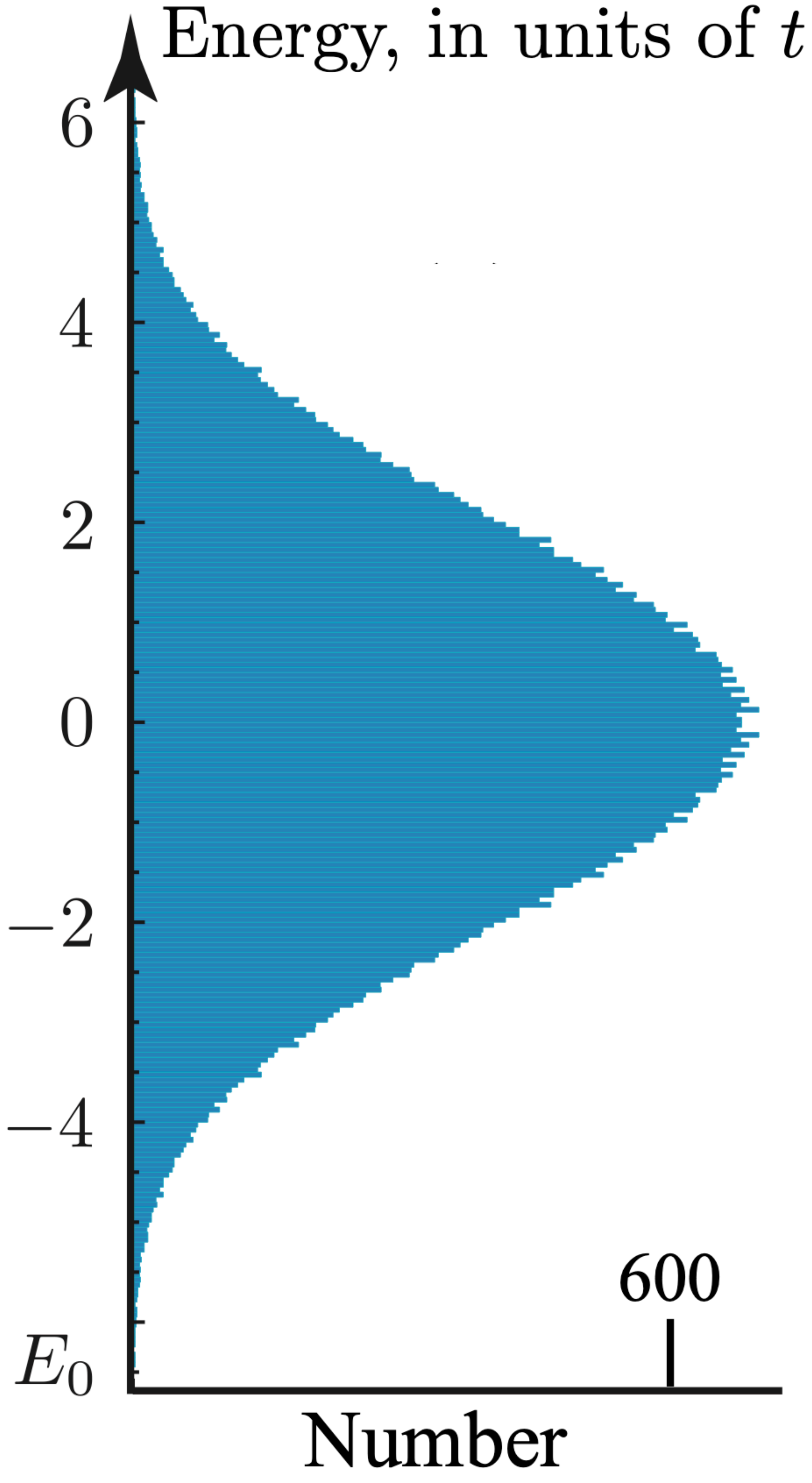


$$S(T \to 0) = N\gamma T$$

$$\gamma = \frac{\pi^2}{3} \rho_0$$

Many-body density of states

$$D(E) = \sum_i \delta(E - E_i); \quad E_0 + E_i \Rightarrow \text{Many body eigenvalue}$$



For random matrix model: $E_0 + E_i = \sum_\alpha n_\alpha \varepsilon_\alpha$ $n_\alpha = 0, 1,$ occupation number

Random matrix model

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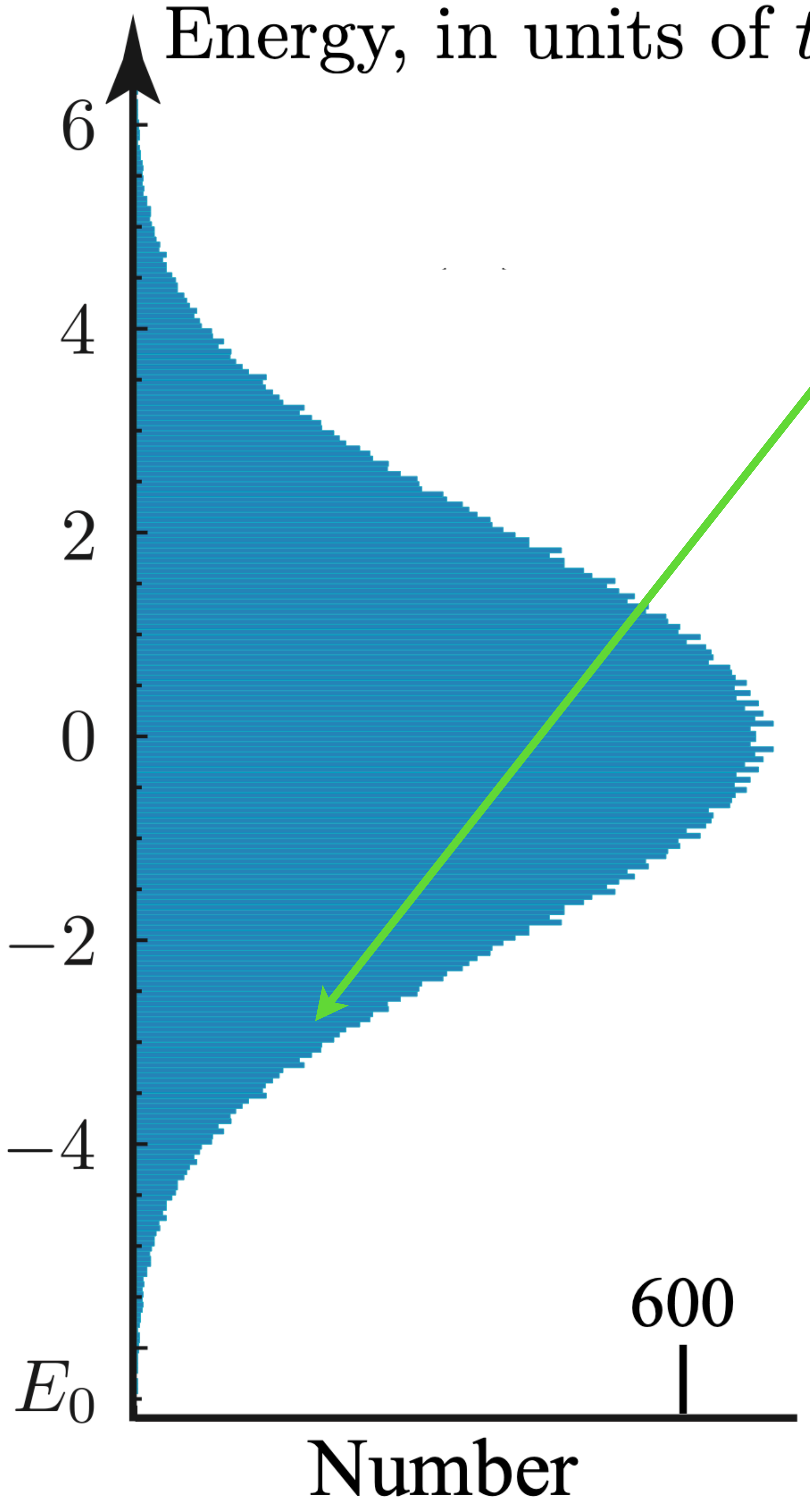

$$D(E) \sim e^{S(E)}$$
$$= e^{\sqrt{2N\gamma E}}$$
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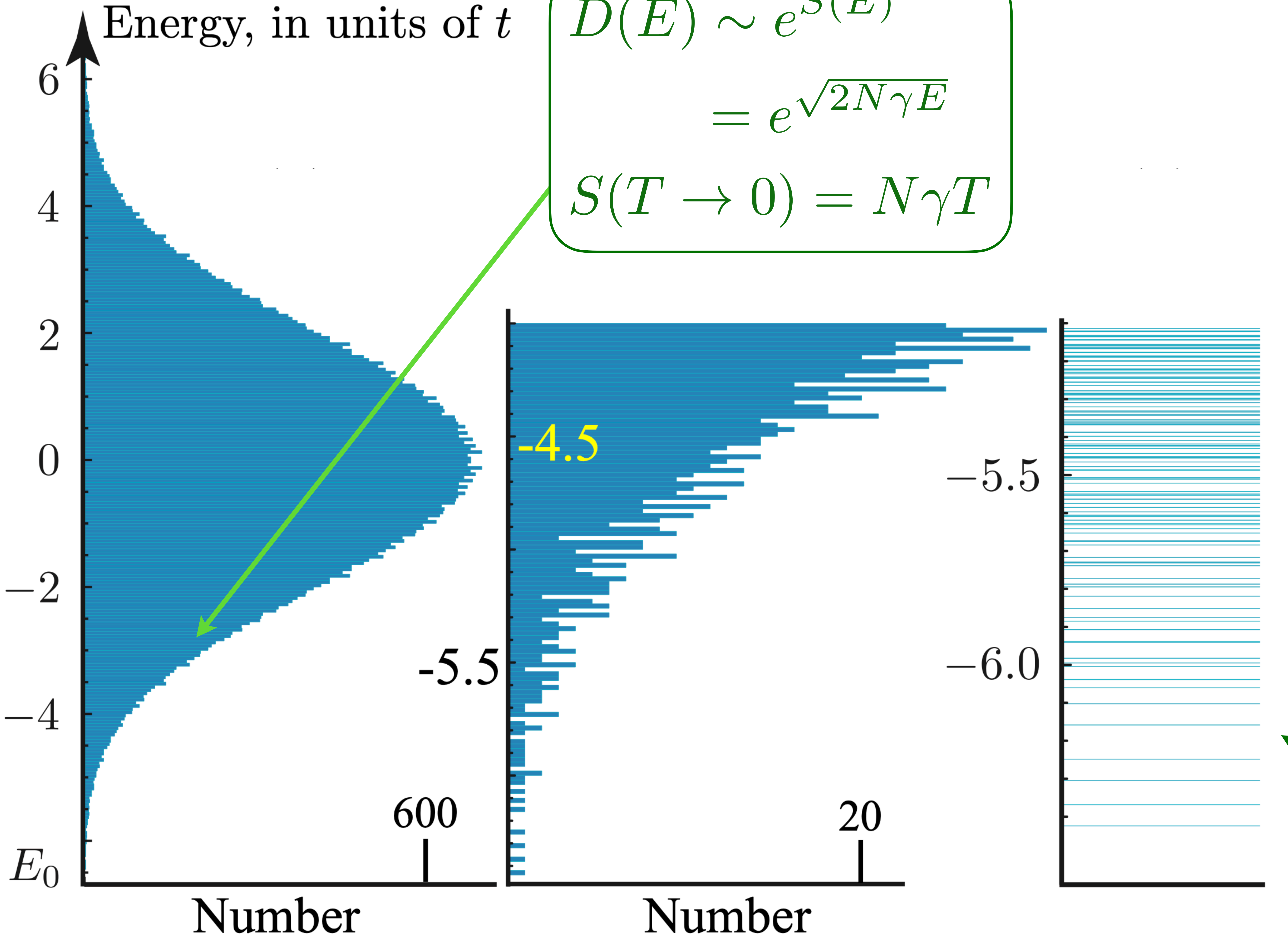


$D(E) \sim N$

Random matrix model

The Sachdev-Ye-Kitaev (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))

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta=1}^{N} U_{\alpha\beta;\gamma\delta}\, c_\alpha^\dagger c_\beta^\dagger c_\gamma c_\delta - \mu \sum_\alpha c_\alpha^\dagger c_\alpha$$

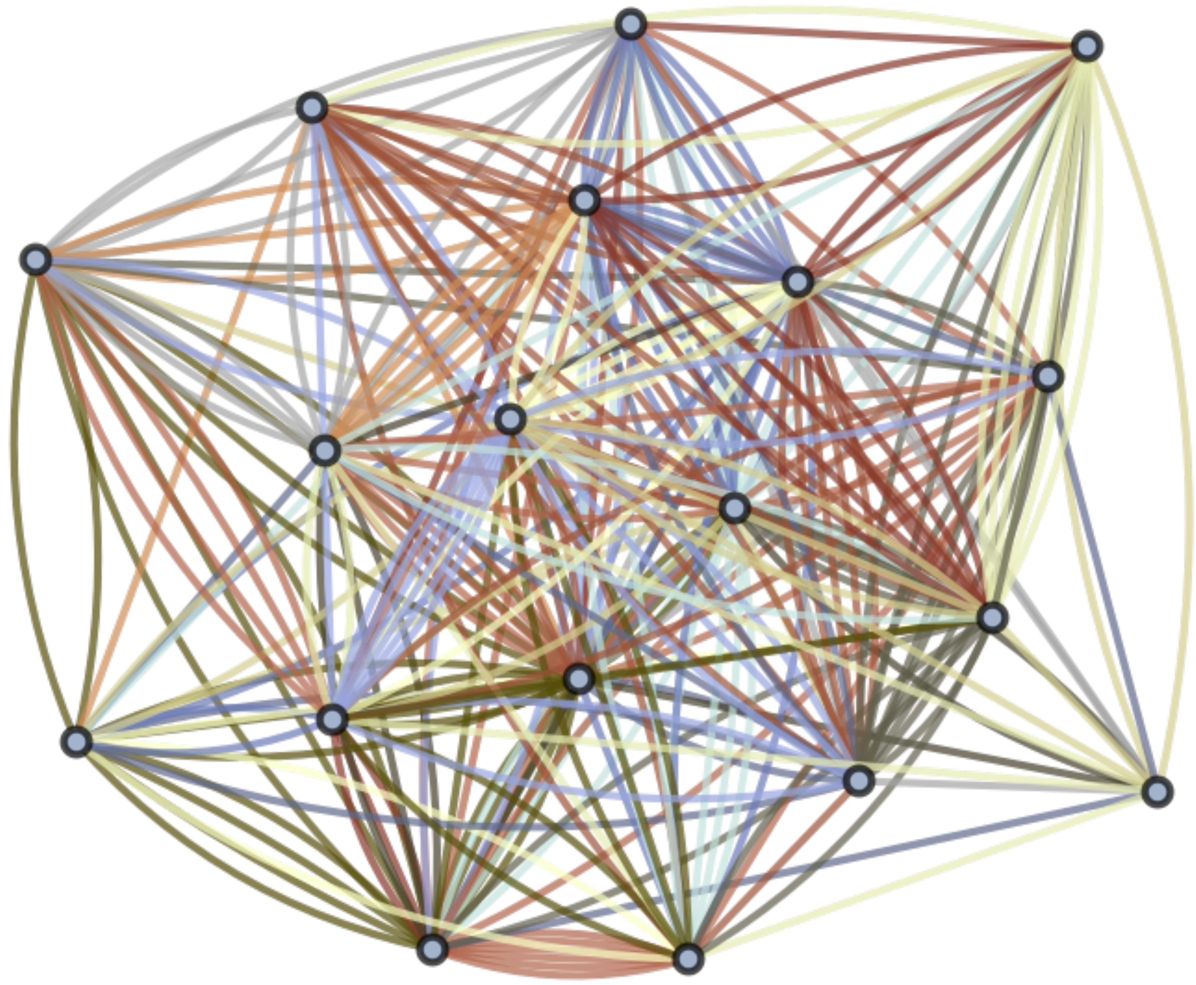
$$c_\alpha c_\beta + c_\beta c_\alpha = 0 \quad , \quad c_\alpha c_\beta^\dagger + c_\beta^\dagger c_\alpha = \delta_{\alpha\beta}$$

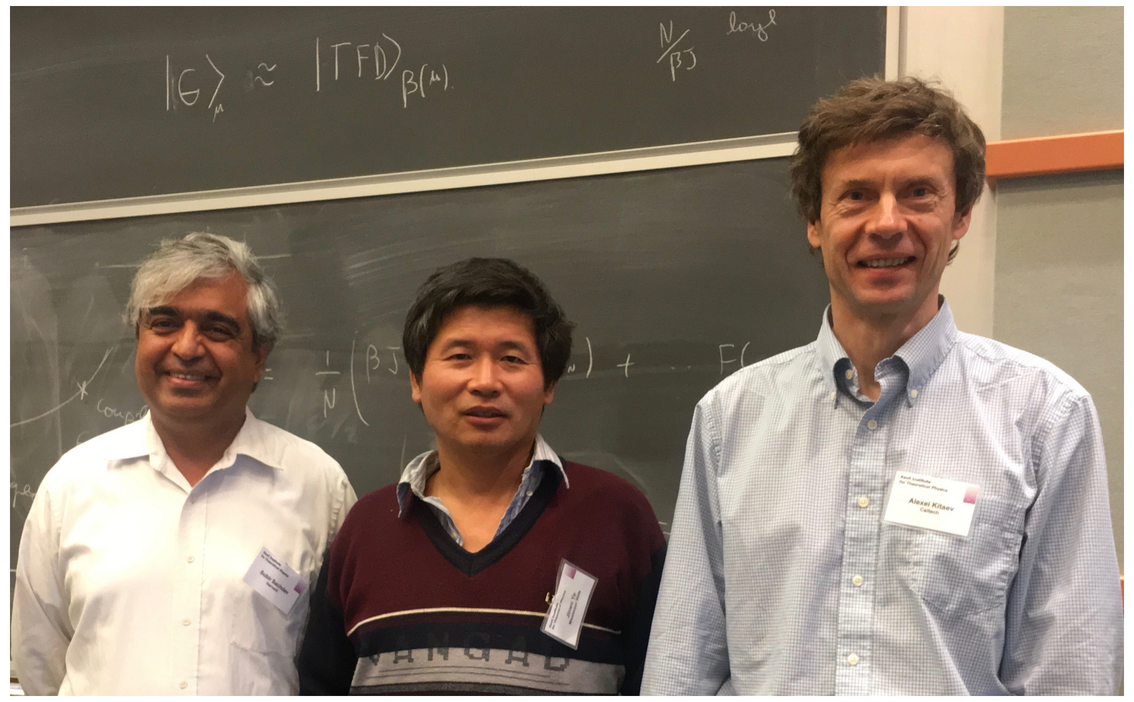
$$\mathcal{Q} = \frac{1}{N} \sum_\alpha c_\alpha^\dagger c_\alpha$$

$U_{\alpha\beta;\gamma\delta}$ are independent random variables with $\overline{U_{\alpha\beta;\gamma\delta}} = 0$ and $\overline{|U_{\alpha\beta;\gamma\delta}|^2} = U^2$
$N \to \infty$ yields critical strange metal.

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

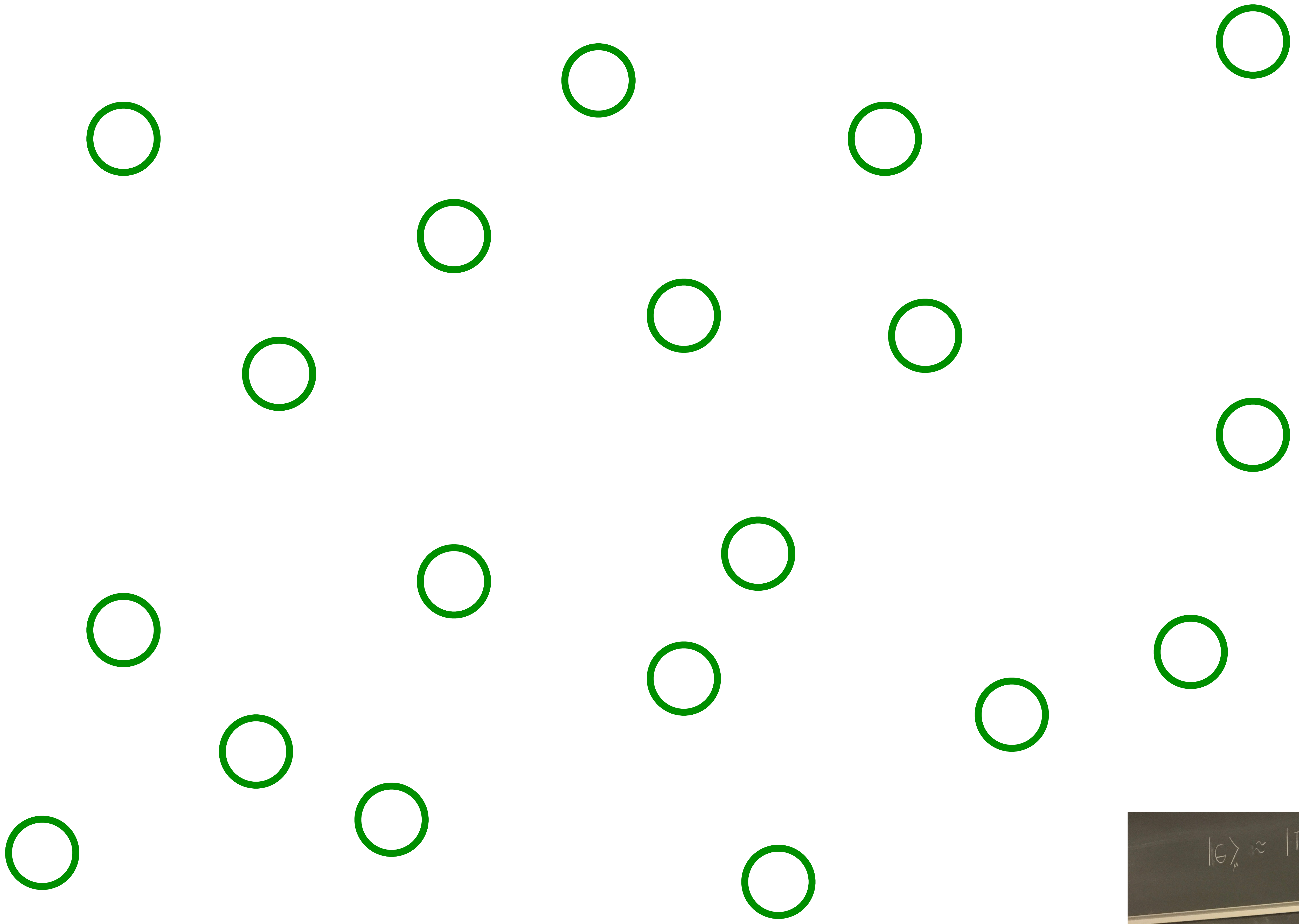
A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)



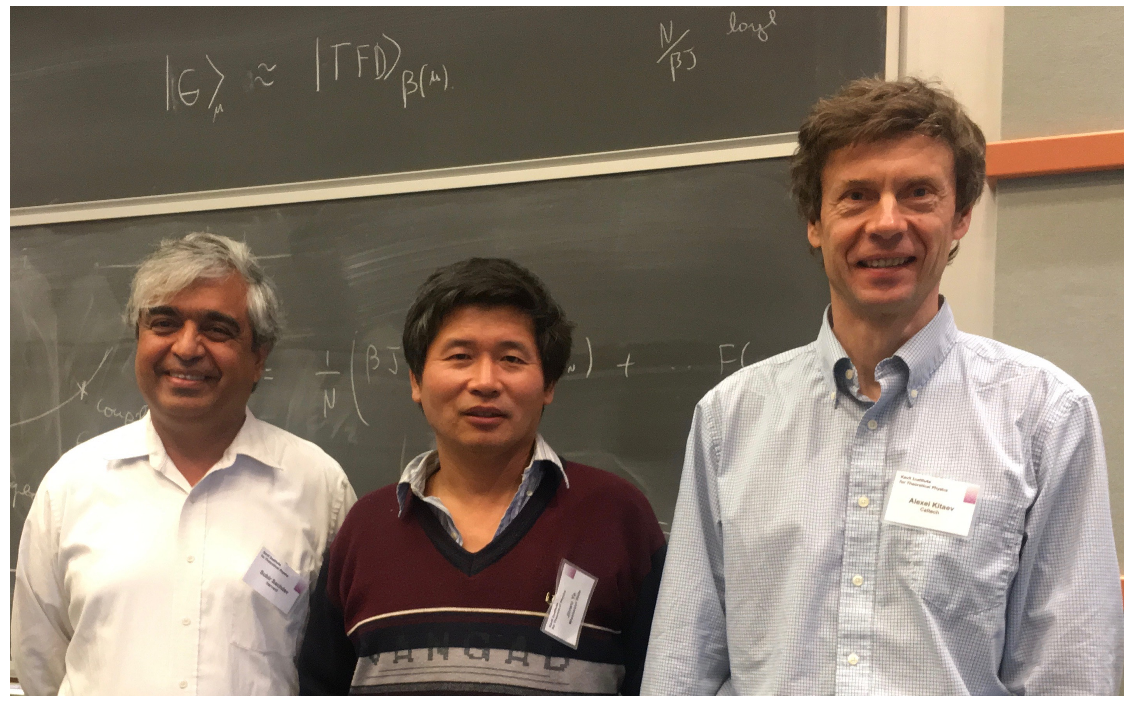


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Pick a set of random positions



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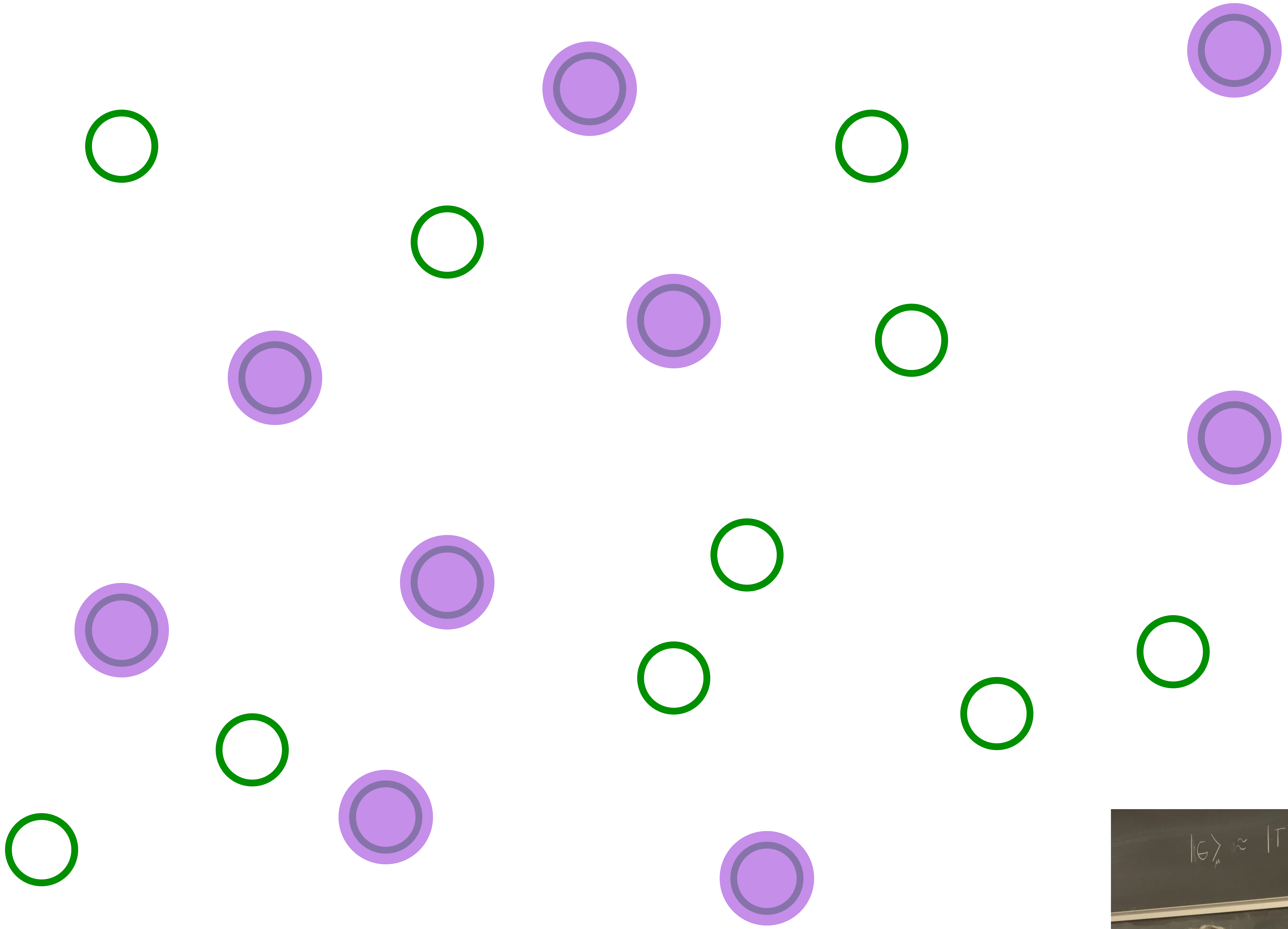
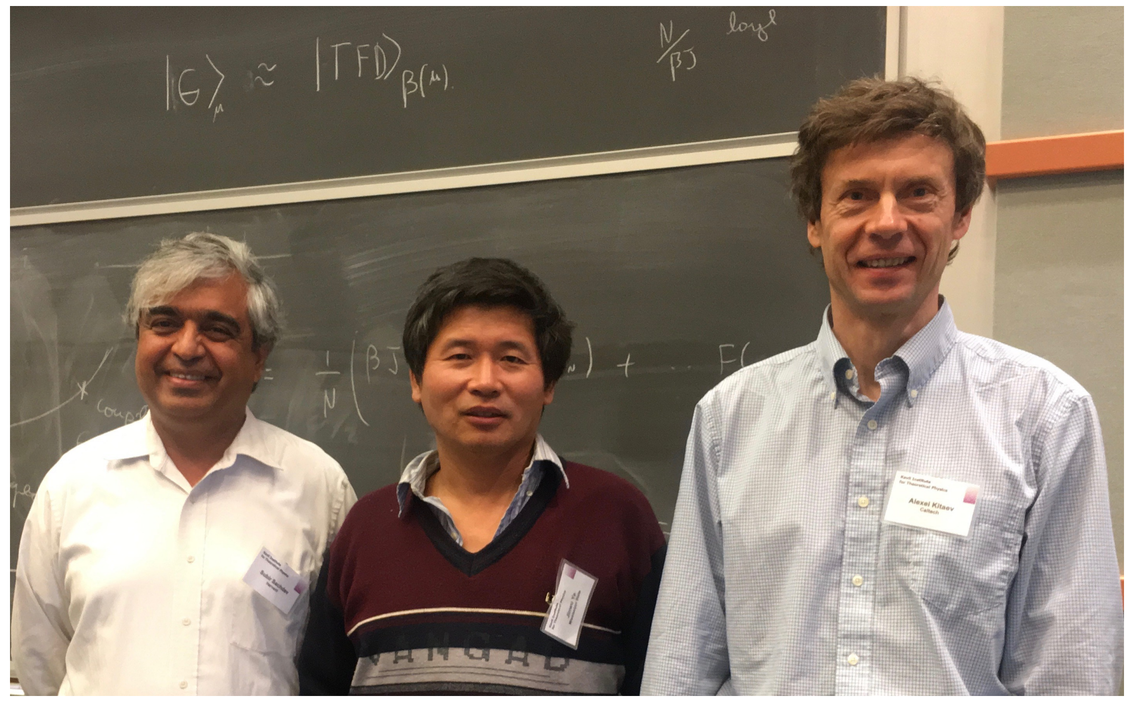


Place electrons randomly on some sites



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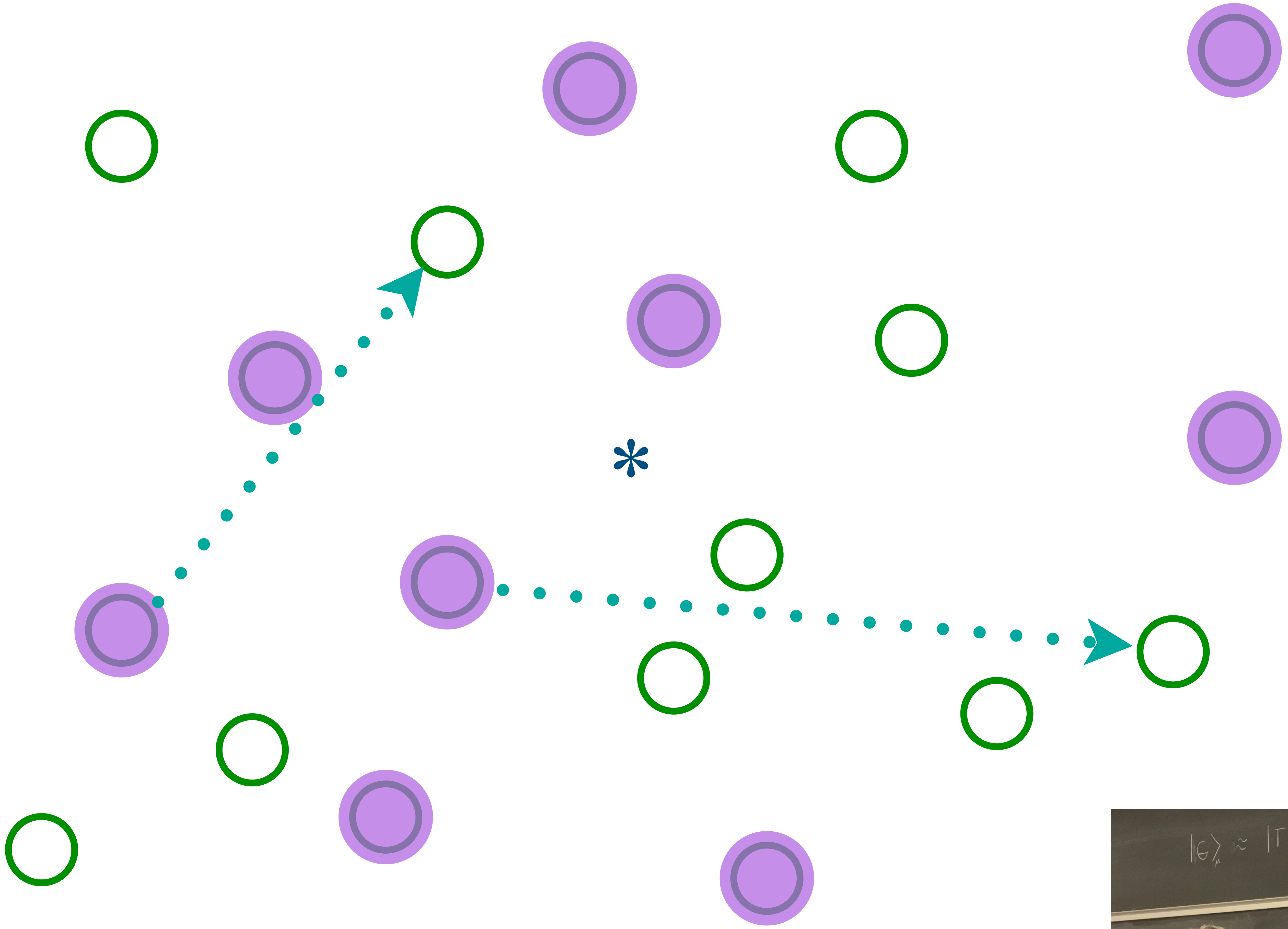

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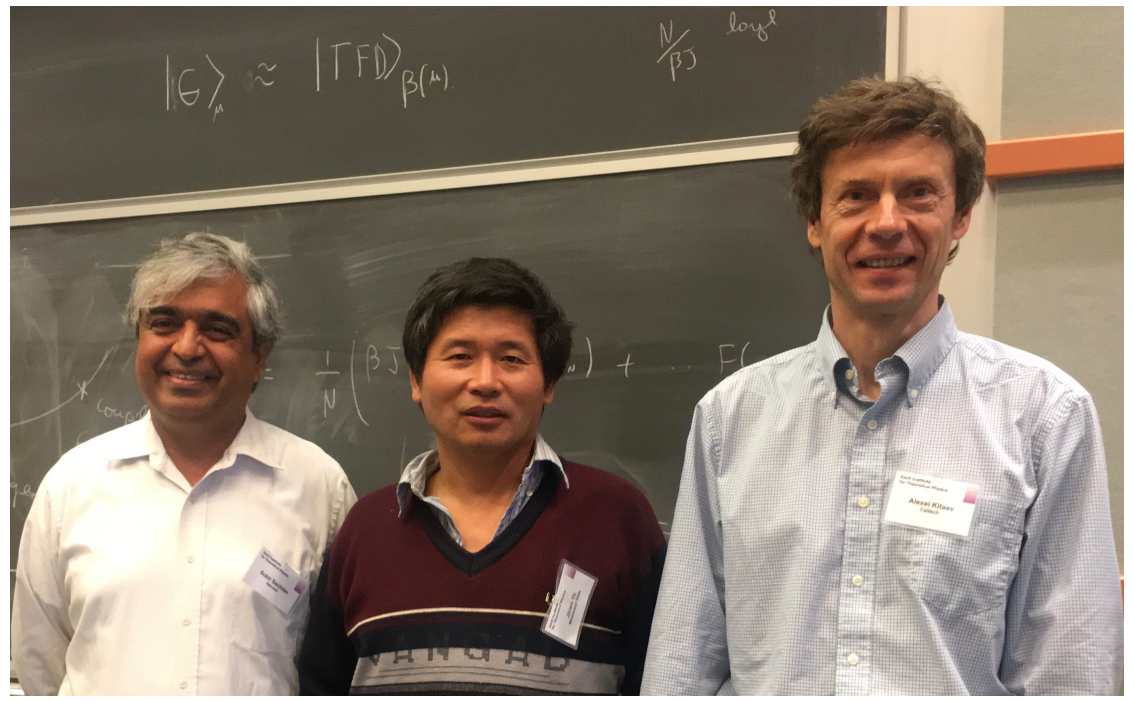

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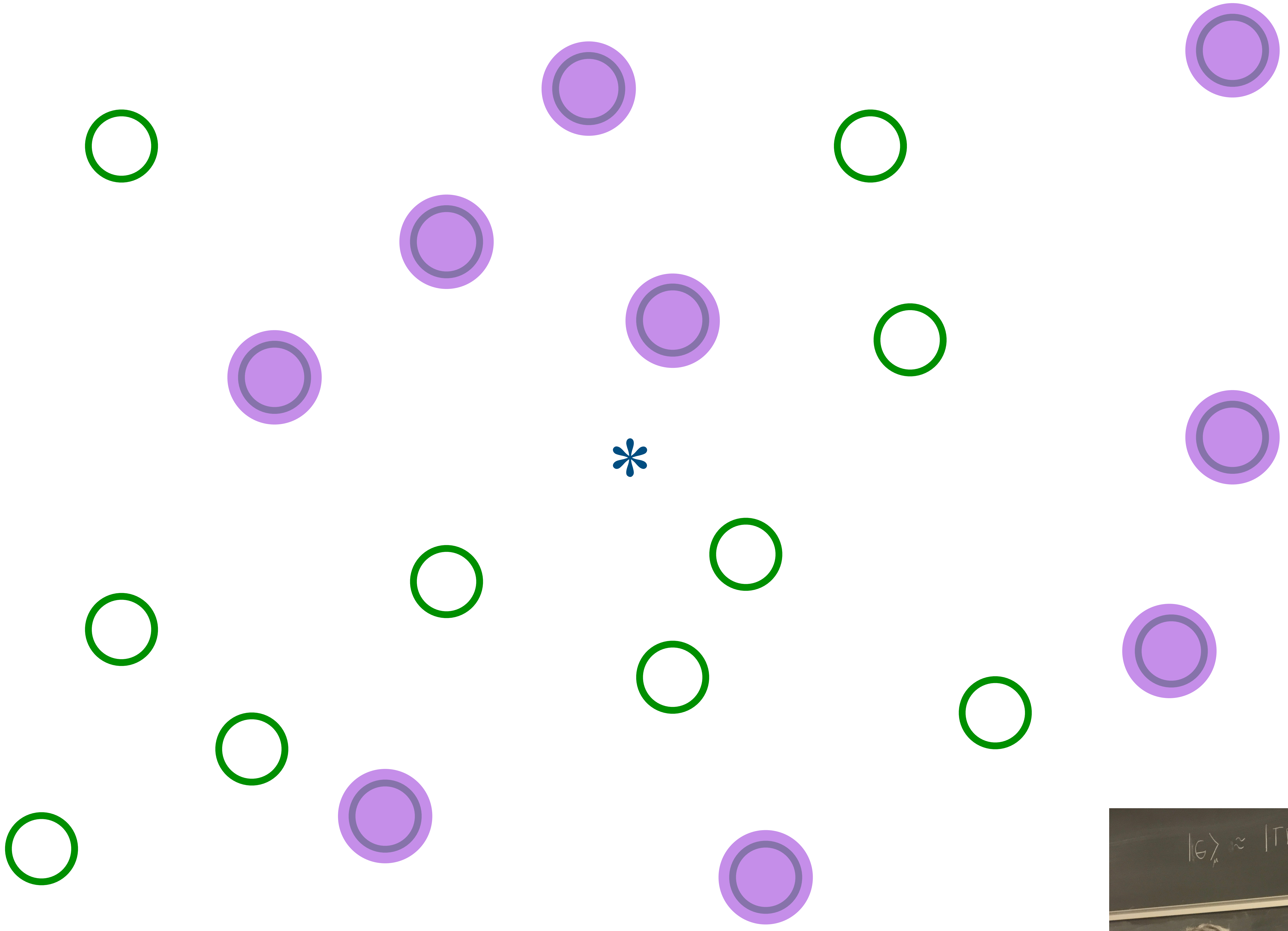
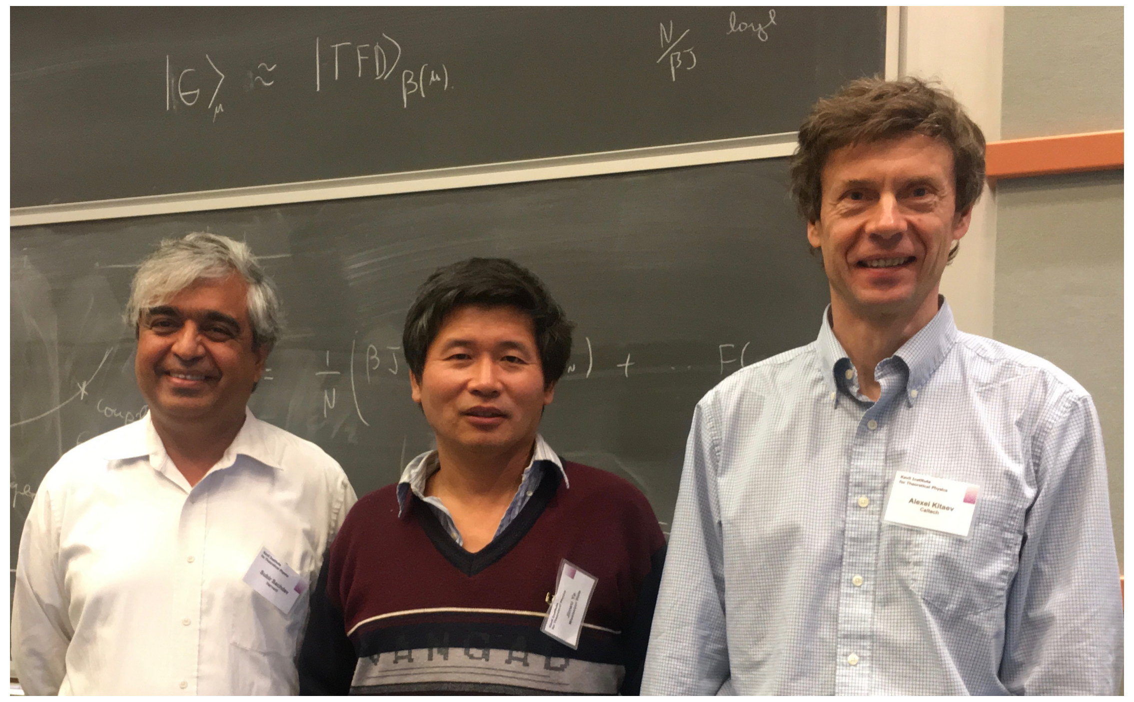


Entangle electrons pairwise randomly



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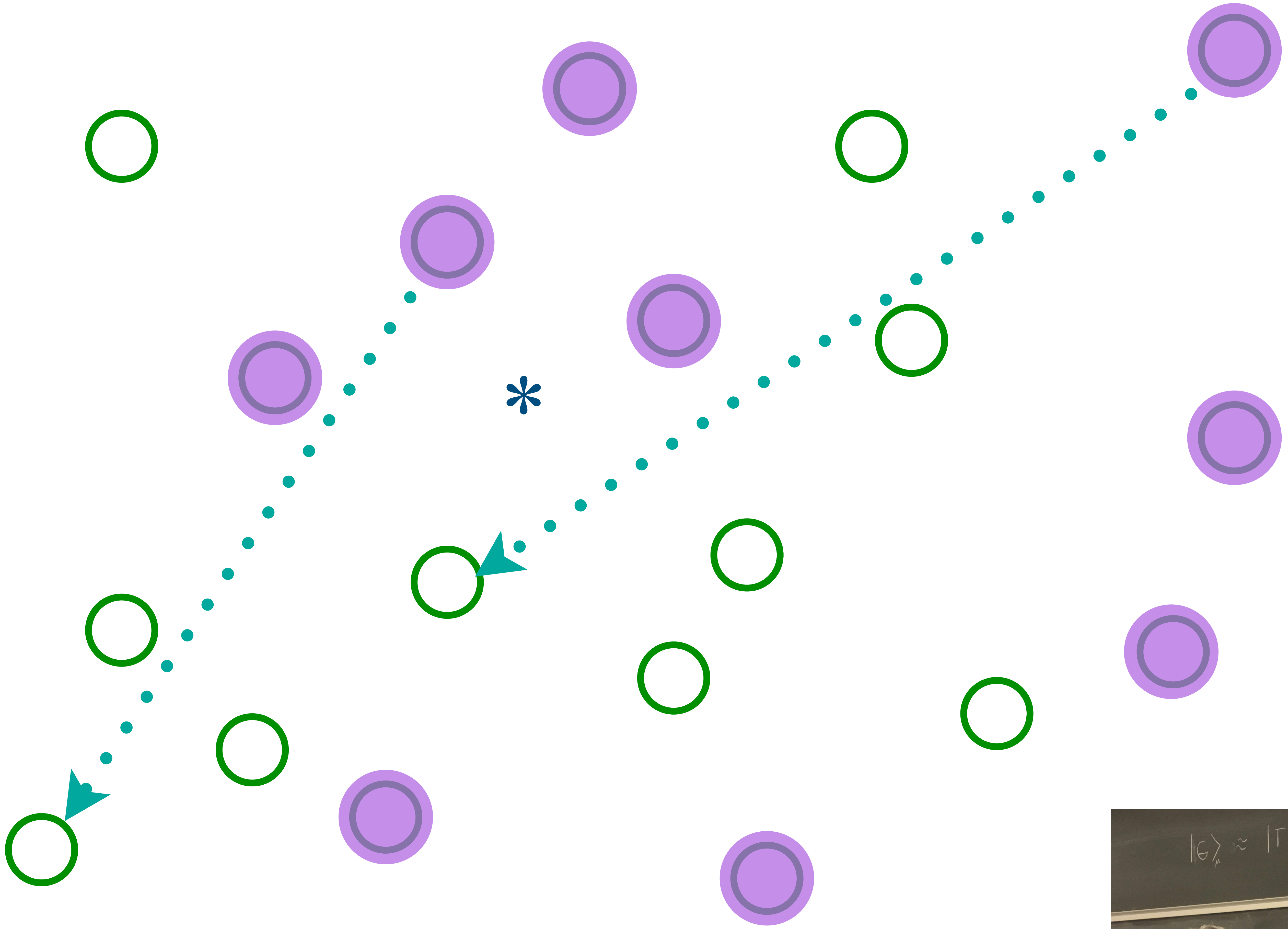

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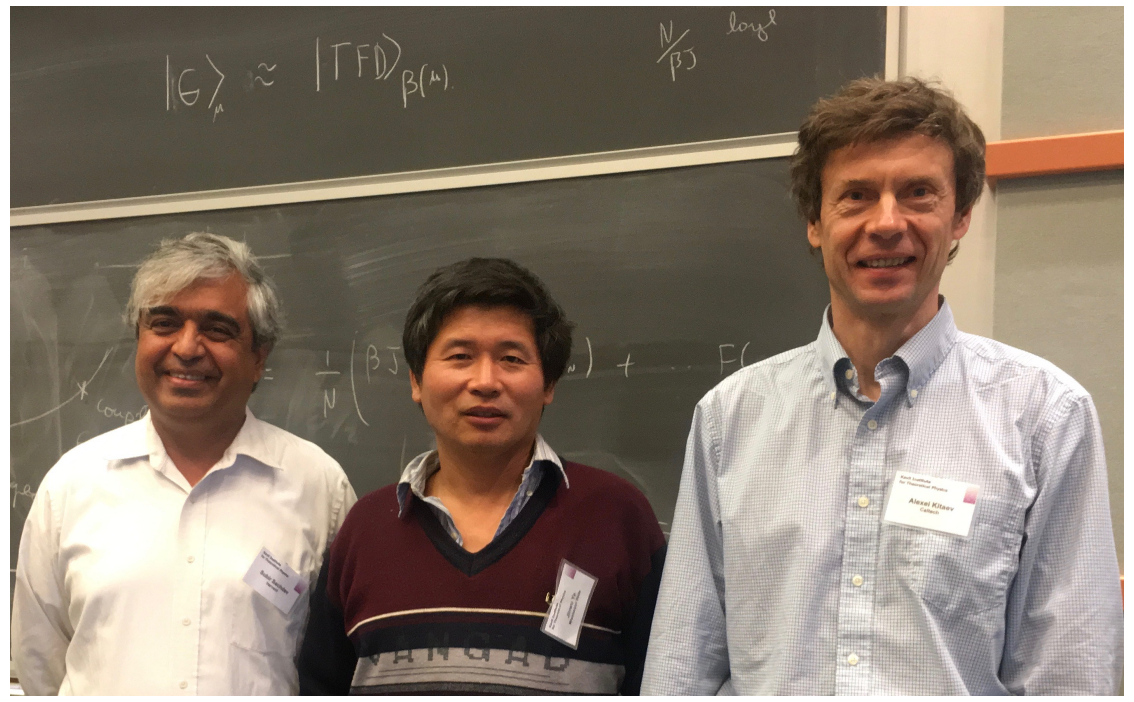

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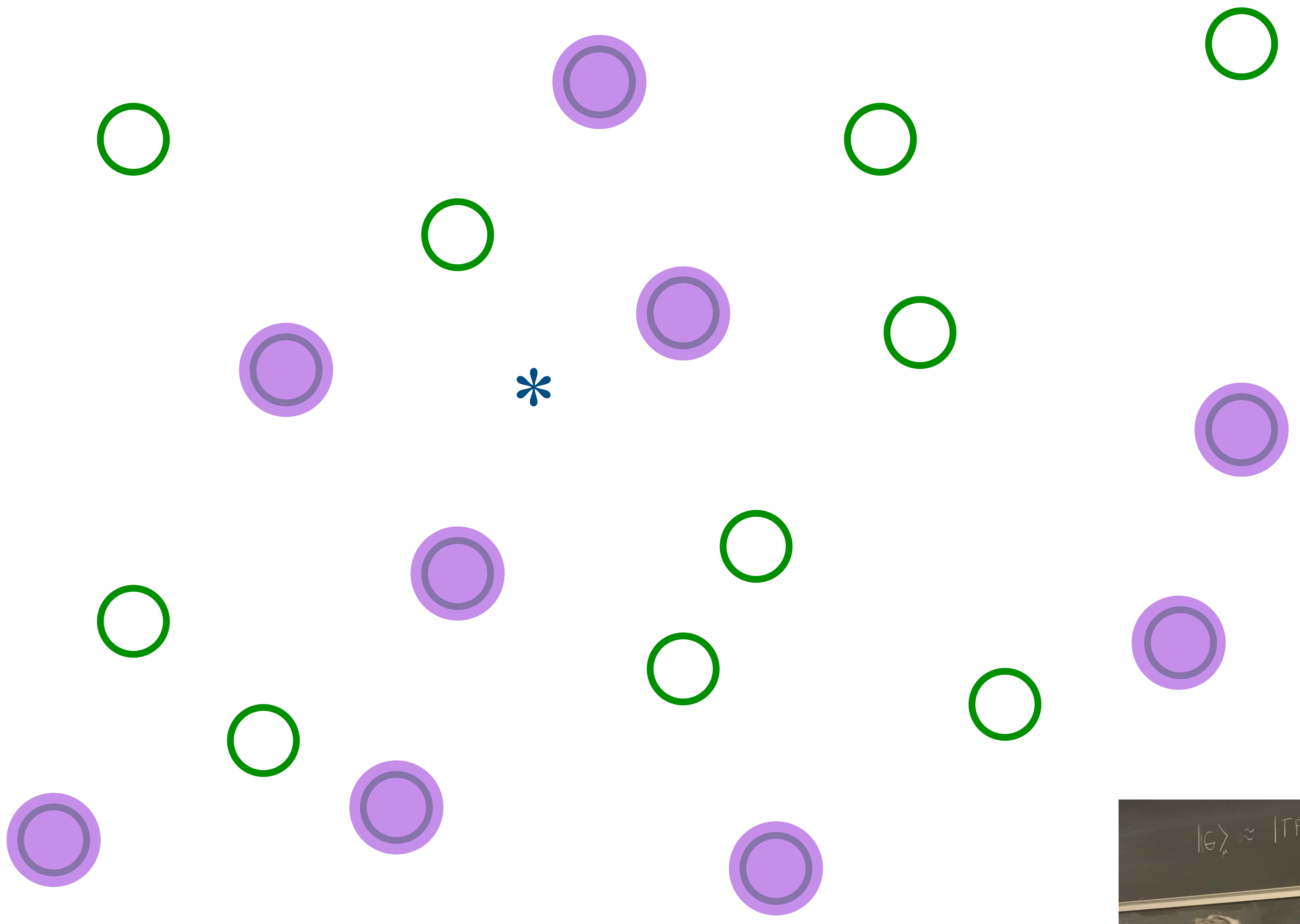

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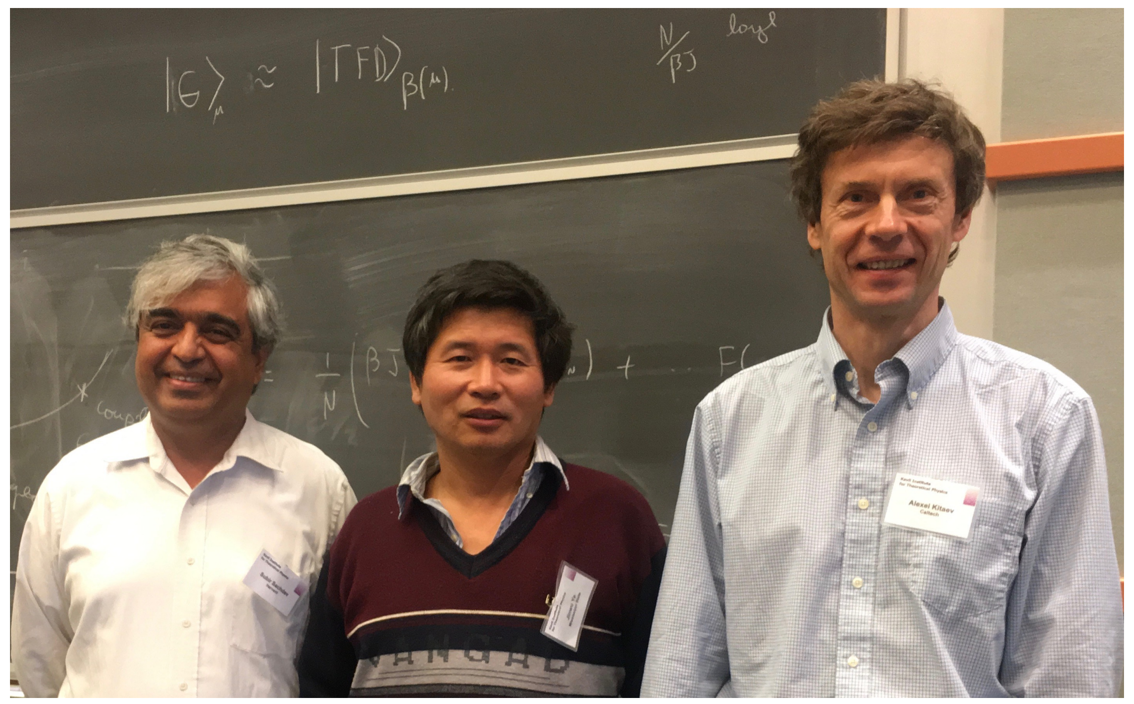

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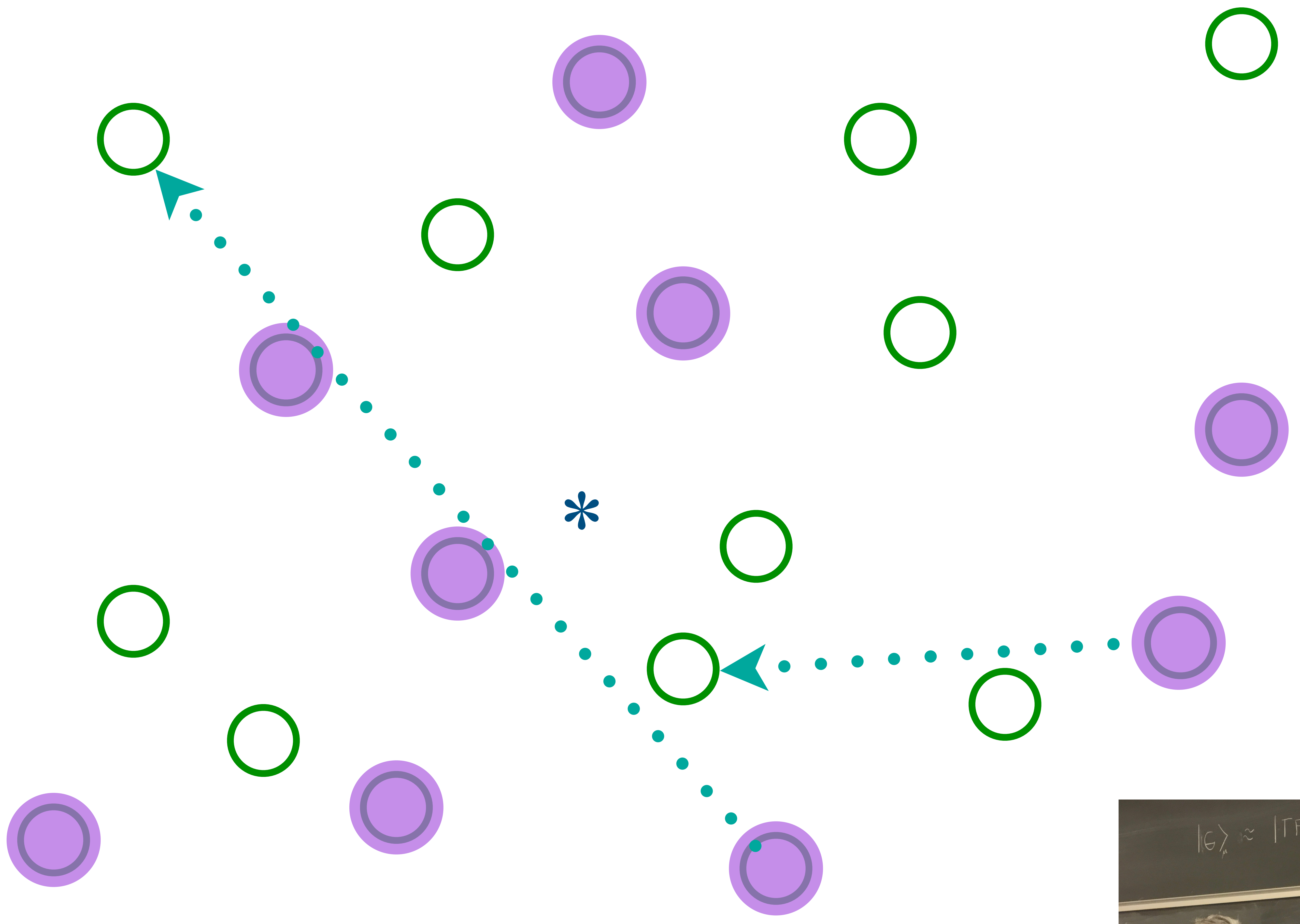

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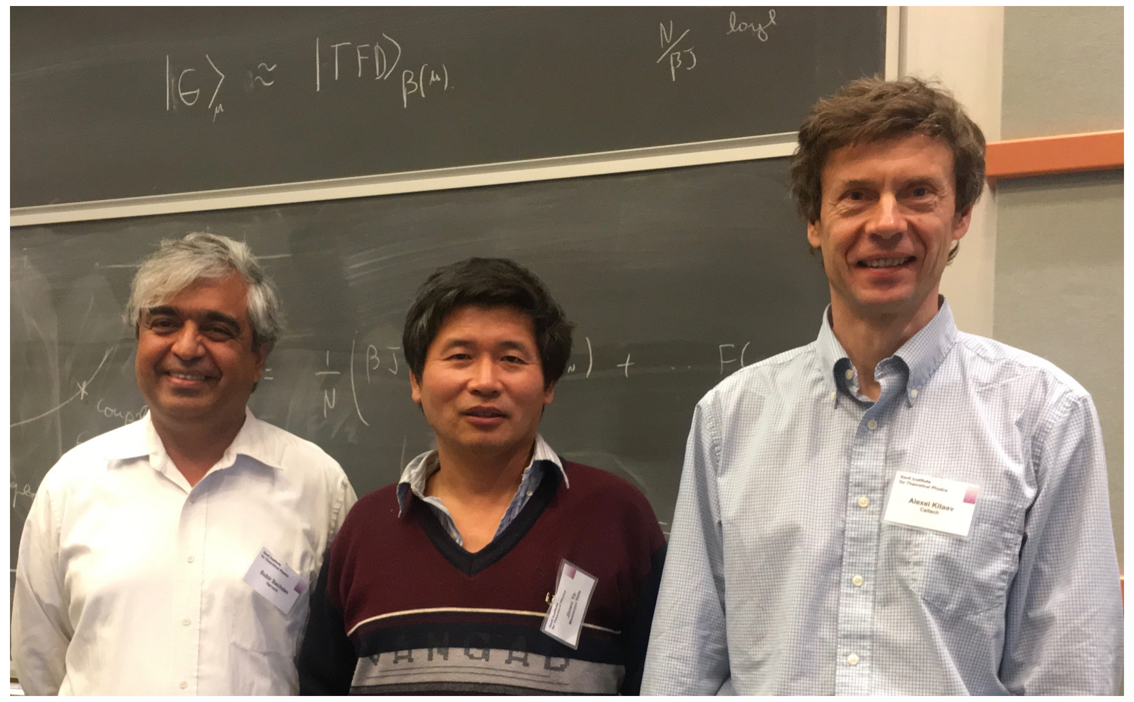

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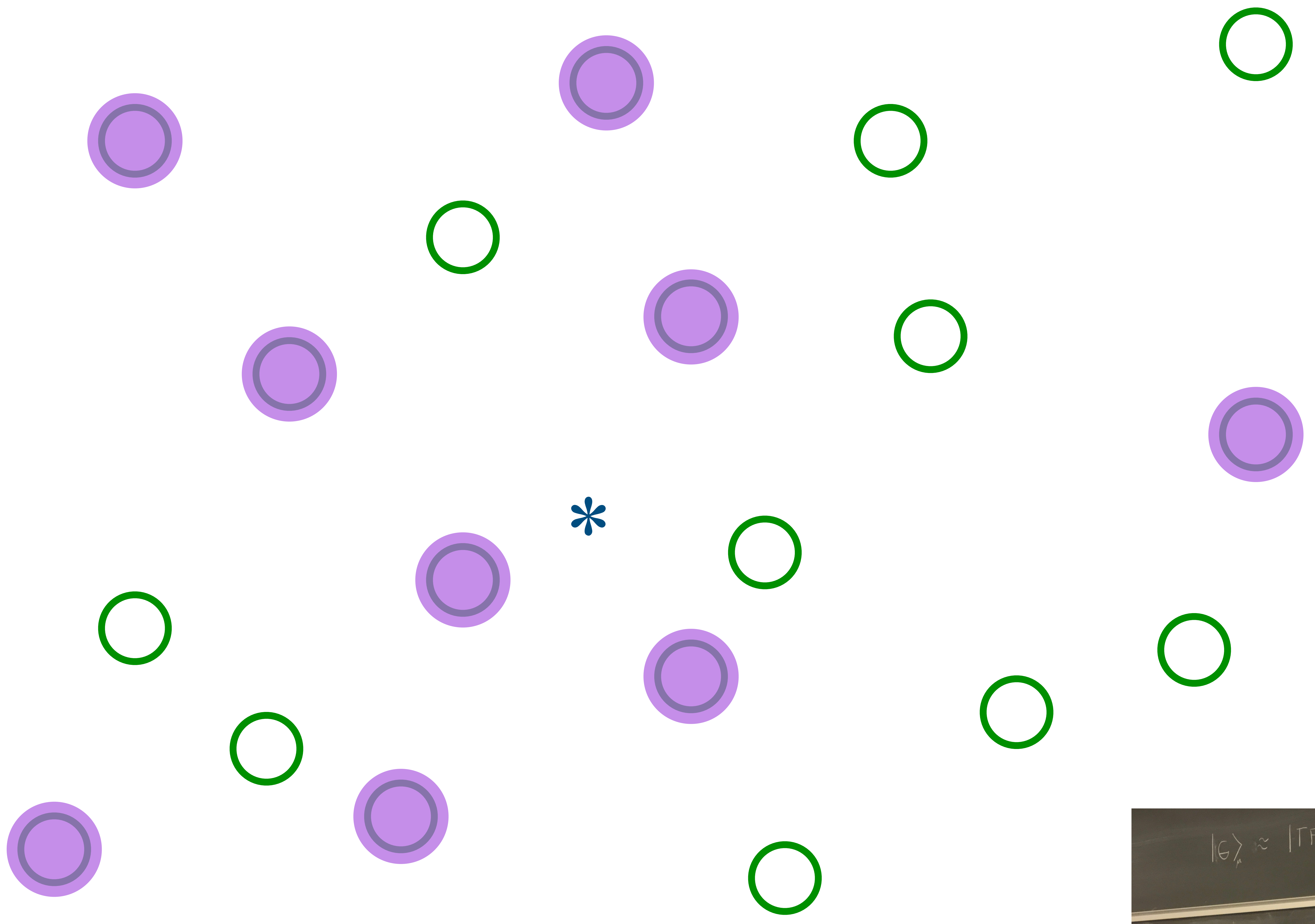

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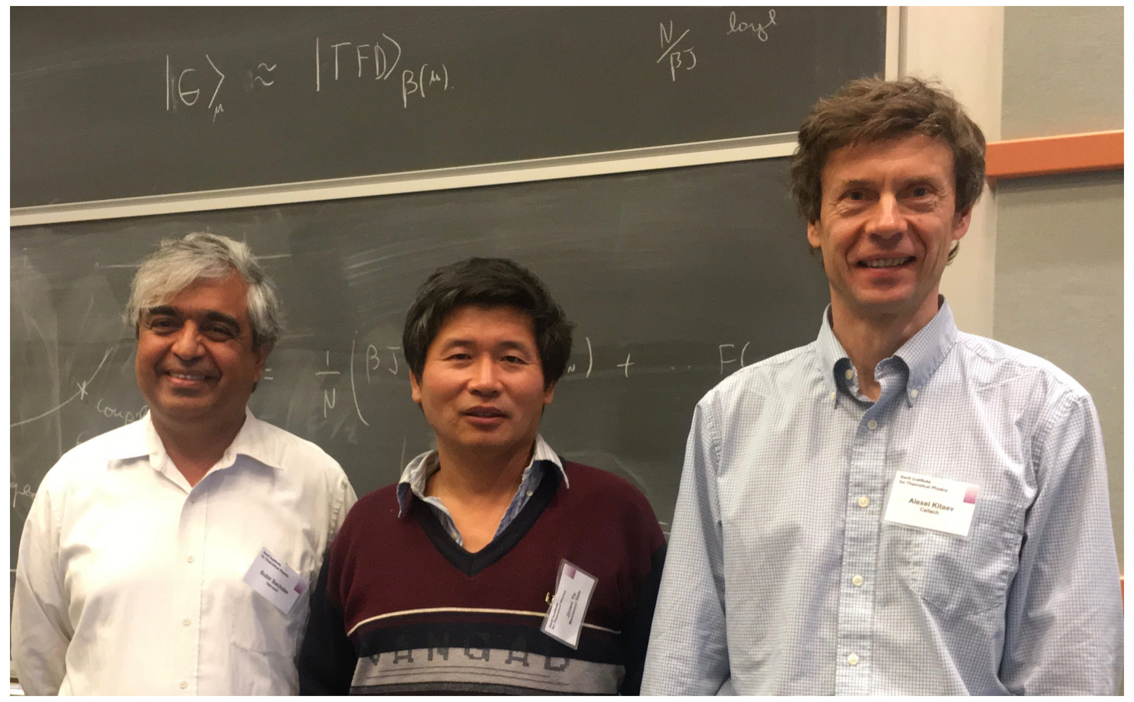

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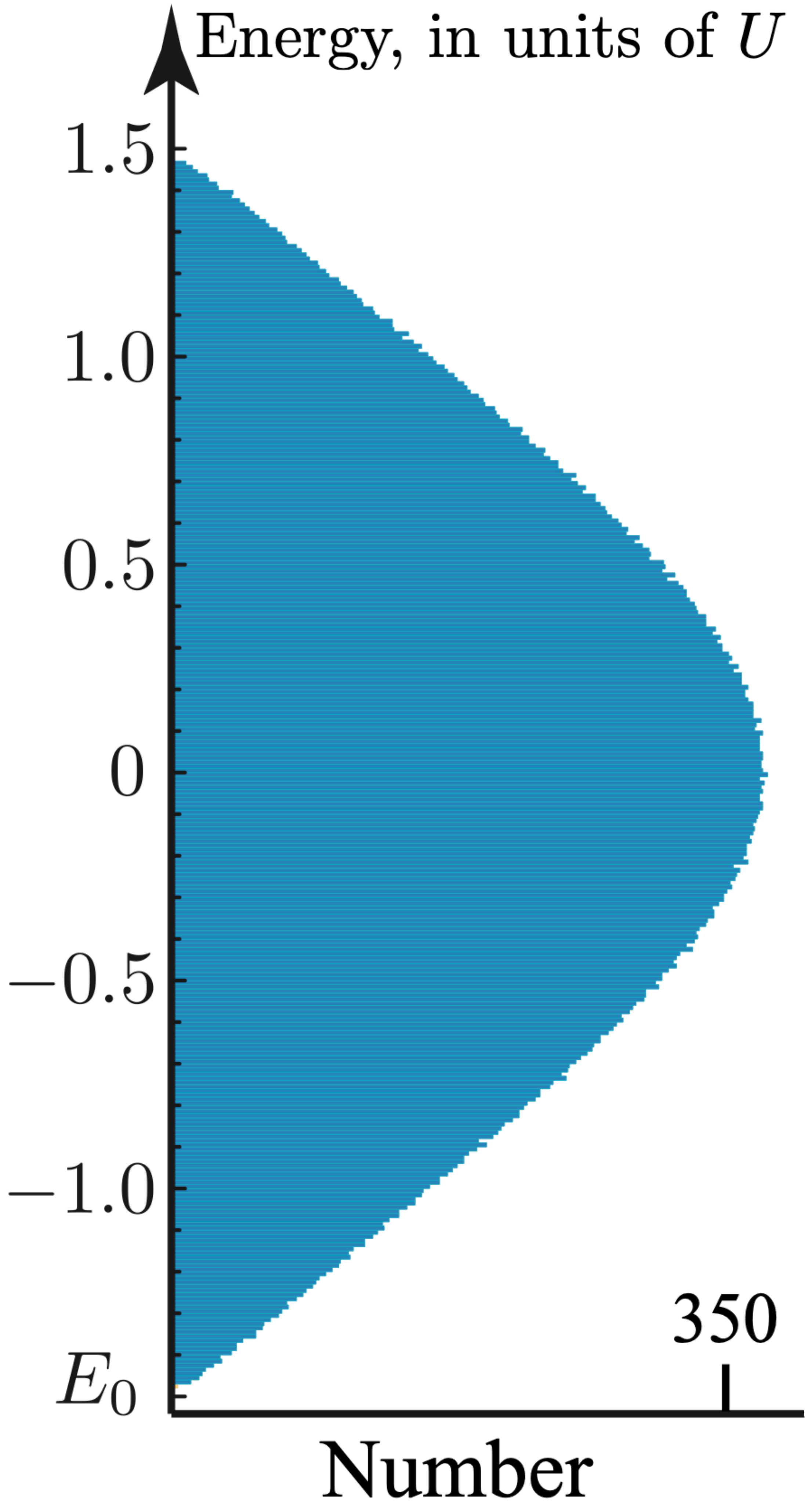

Complex SYK model

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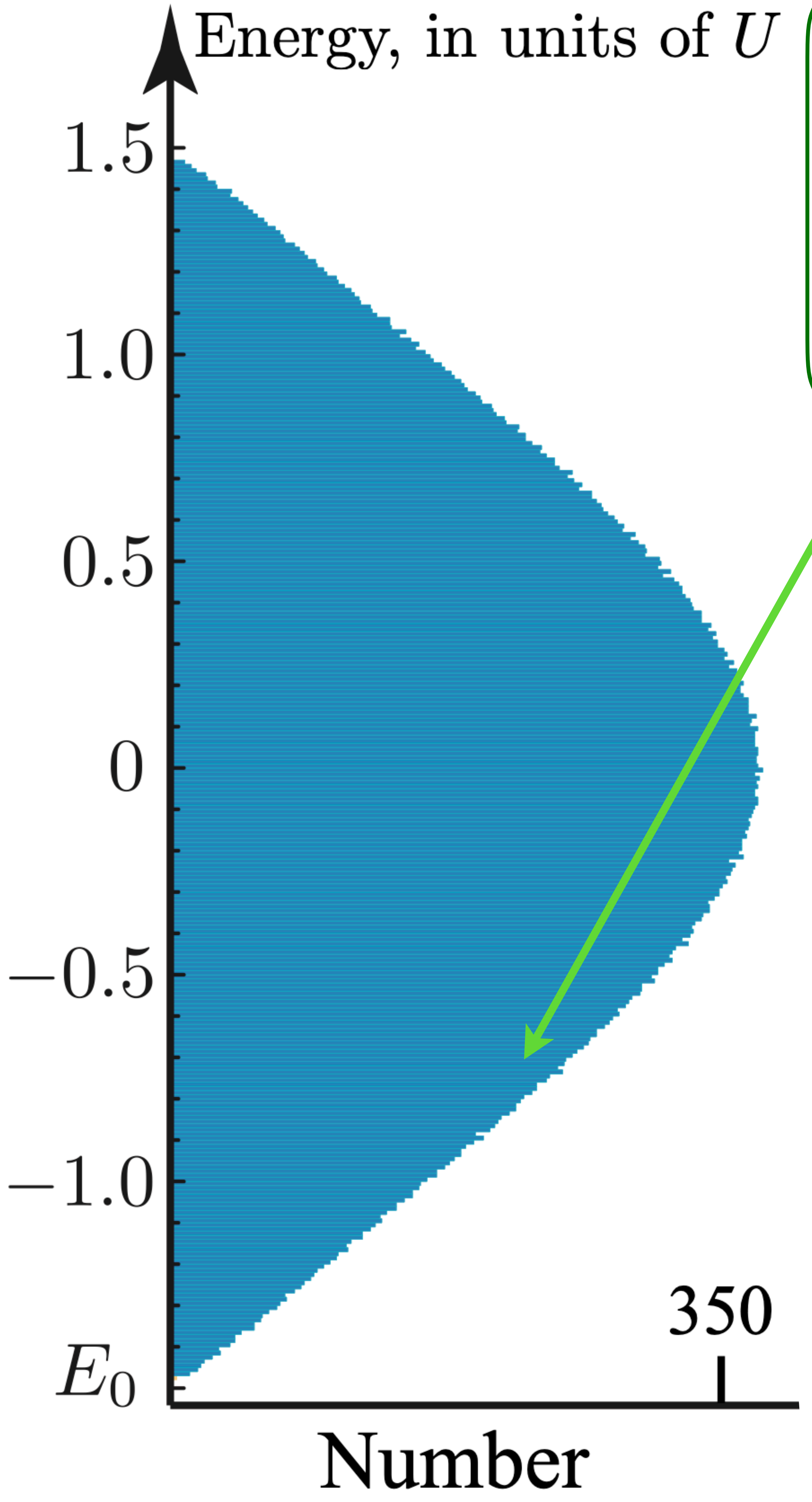

$$D(E) \sim e^{S(E)}$$
$$= e^{Ns_0 + \sqrt{2N\gamma E}}$$
$$S(T \to 0) = N(s_0 + \gamma T)$$

$s_0 = 0.464848\ldots$

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

Complex SYK model

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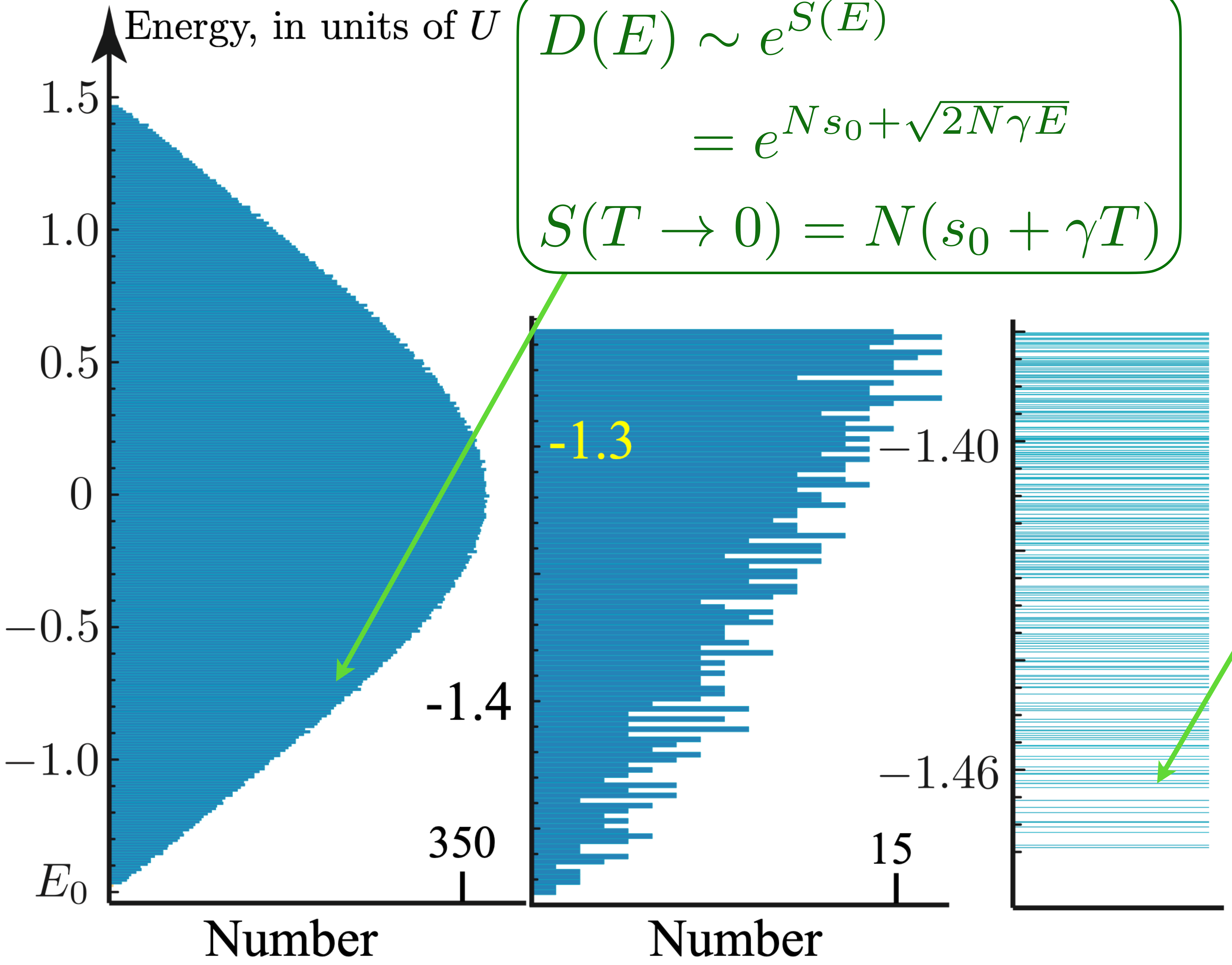

$$D(E) \sim 2\, e^{N s_0} \sqrt{2N\gamma E}$$

No quasiparticle decomposition: wavefunctions change chaotically from one state to the next.

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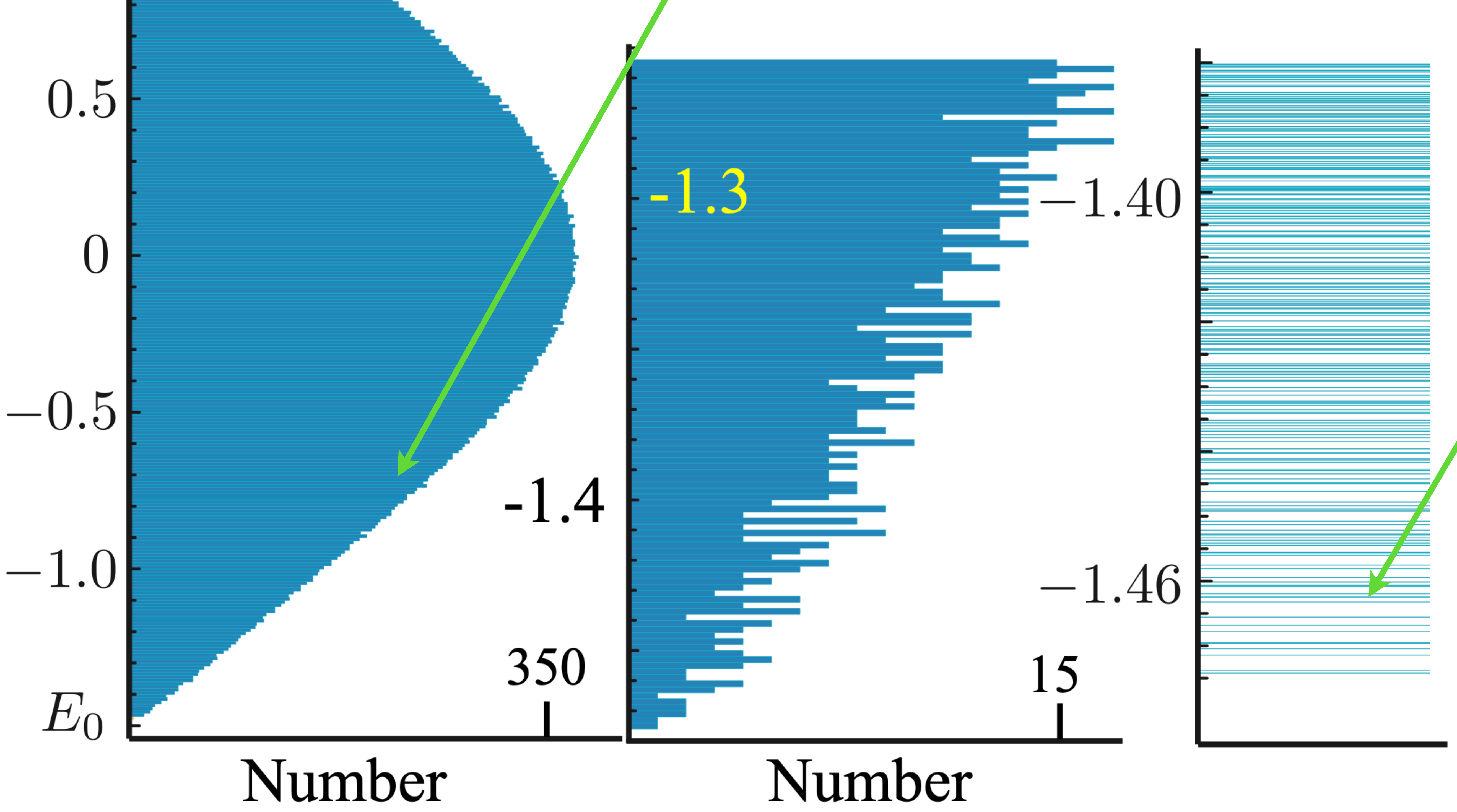
$$D(E) \sim 2\, e^{Ns_0} \sinh(\sqrt{2N\gamma E})$$

$$e^{-F(T)/T} = \int_0^\infty dE D(E) e^{-E/T}$$
$$S(T) = -\partial F / \partial T$$

$$D(E) \sim 2\, e^{Ns_0} \sqrt{2N\gamma E}$$



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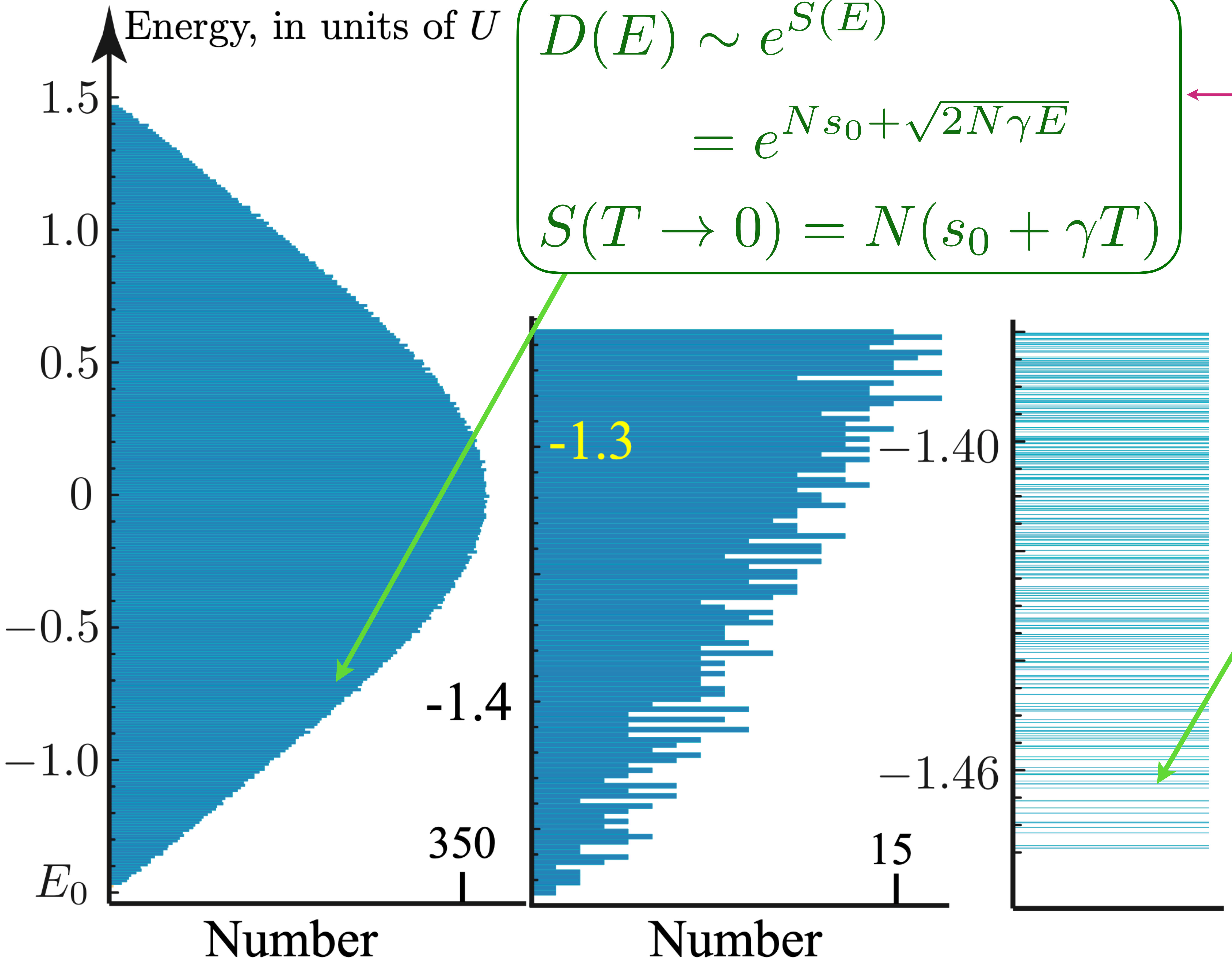

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$$D(E) \sim 2\, e^{Ns_0} \sinh(\sqrt{2N\gamma E})$$
$$S(T) = N(s_0 + \gamma T) - \frac{3}{2} \ln\left(\frac{U}{T}\right)$$

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$$= \exp\Big(S_{BH}\Big) \times \Bigg(\quad ....????... \quad \Bigg)$$

Gibbons, Hawking (1977)
Chambin, Emparan, Johnson, Myers (1999)

$$S_{BH}(T \to 0, \mathcal{Q}) = \frac{A(T)c^3}{4G\hbar} = \frac{A_0 c^3}{4G\hbar}\left(1 + \frac{2(\pi A_0)^{1/2}T}{\hbar c}\right)$$

A_0 is the area of the charged black hole horizon at $T = 0$.
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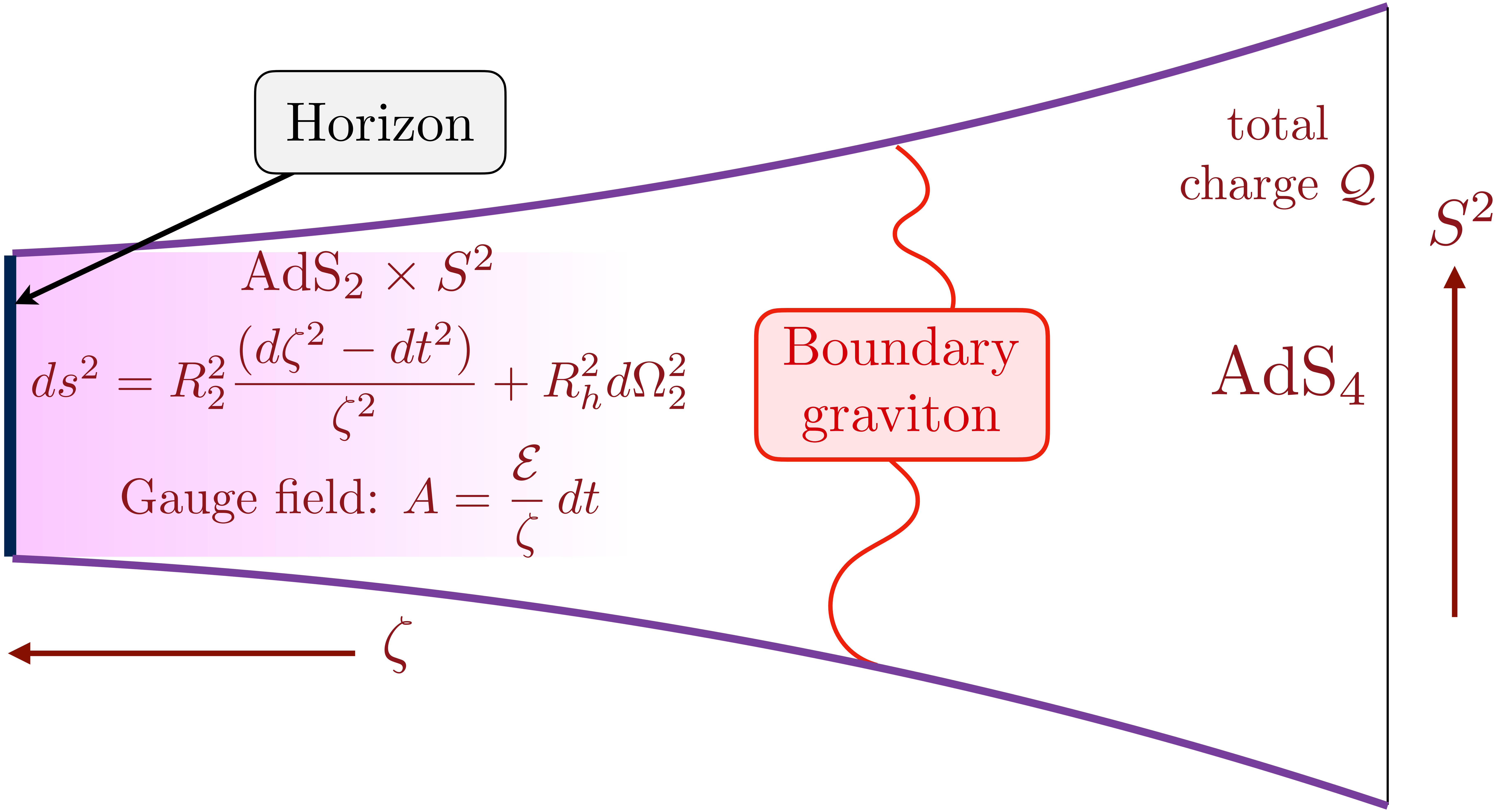
Note the similarity to the large N entropy of the SYK model !
(along with other similarities) Sachdev PRL 2010

Reissner-Nordstrom black hole of Einstein-Maxwell theory



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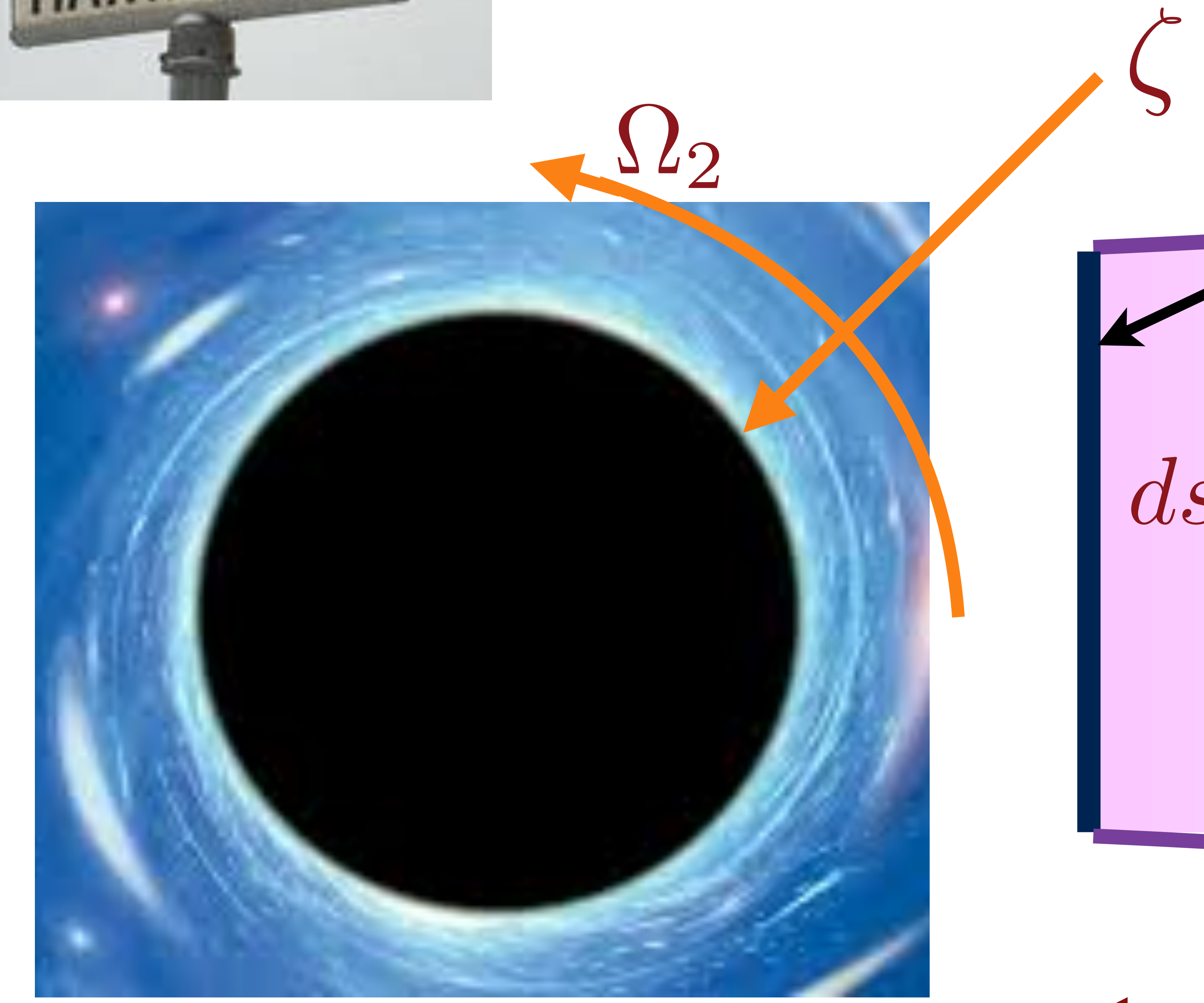

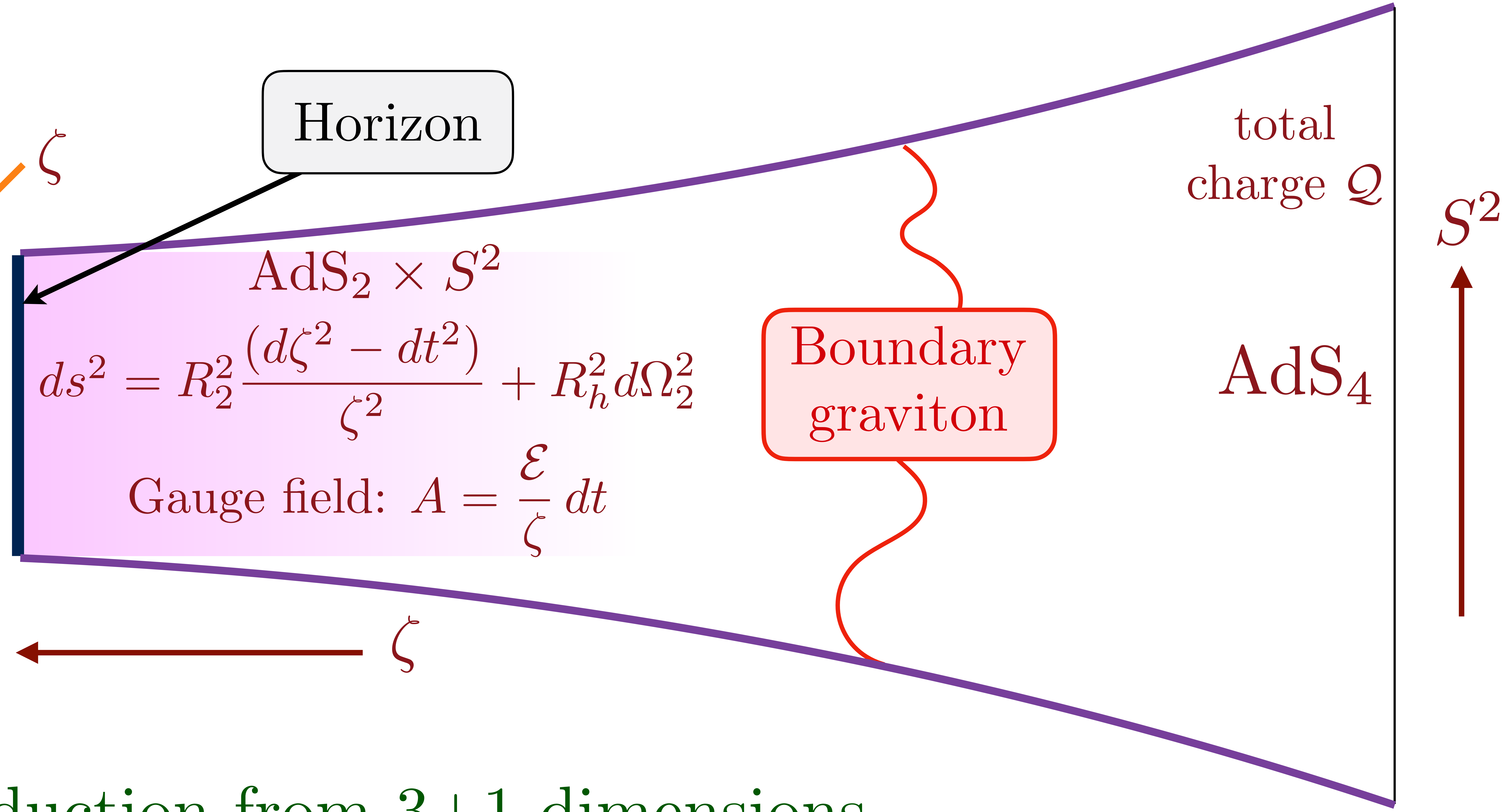

Dimensional reduction from 3+1 dimensions to 1+1 dimensions (AdS_2) at low energies!

Thermodynamics of quantum black holes with charge $\mathcal{Q}$:

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$$\approx \int \mathcal{D}g_{\mu\nu}\mathcal{D}A_\mu \exp\left(-\frac{1}{\hbar}\,\mathcal{S}^{(1+1)}_{\text{JT gravity of AdS}_2\text{+boundary graviton}}[g_{\mu\nu},A_\mu]\right)$$

$$S_{BH}(T\to 0,\mathcal{Q}) = \frac{A(T)c^3}{4G\hbar} = \frac{A_0c^3}{4G\hbar}\left(1+\frac{2(\pi A_0)^{1/2}T}{\hbar c}\right)$$

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Maldacena, Stanford, Yang (2016)

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$$= \int \mathcal{D}f(\tau)\mathcal{D}\phi(\tau) \exp\left(-\frac{1}{\hbar}\mathcal{S}_{\text{SYK}}[\text{time reparameterizations } f(\tau), \text{ phase rotations } \phi(\tau)]\right)$$

$$S_{BH}(T \to 0, \mathcal{Q}) = \frac{A(T)c^3}{4G\hbar} = \frac{A_0 c^3}{4G\hbar}\left(1 + \frac{2(\pi A_0)^{1/2}T}{\hbar c}\right)$$

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Sachdev (2010); Kitaev (2015); Sachdev (2015); Bagrets, Altland, Kamenev (2016); Maldacena, Stanford, Yang (2016); Moitra, Trivedi, Vishal (2018) ; Gaikwad, Joshi, Mandal, Wadia (2018); Sachdev (2019); Iliesiu, Turaci (2020)

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$$S(T\to 0,\mathcal{Q}) = S_{BH} - \frac{3}{4}\ln\left(\frac{\hbar c^5}{GT^2}\right)$$

$$S_{BH} = \frac{A(T)c^3}{4G\hbar} = \frac{A_0 c^3}{4G\hbar}\left(1 + \frac{2(\pi A_0)^{1/2}T}{\hbar c}\right)$$

A_0 is the area of the charged black hole horizon at $T=0$, $\mathcal{Q}$ is the black hole charge. The $\ln T$ term is the contribution of the boundary graviton.

(There is also a $-(241/45)\ln(A_0/G)$ correction at $T=0$ A. Sen 2011)

Sachdev (2010); Kitaev (2015); Sachdev (2015); Bagrets, Altland, Kamenev (2016); Maldacena, Stanford, Yang (2016); Moitra, Trivedi, Vishal (2018) ; Gaikwad, Joshi, Mandal, Wadia (2018); Sachdev (2019); Iliesiu, Turaci (2020)

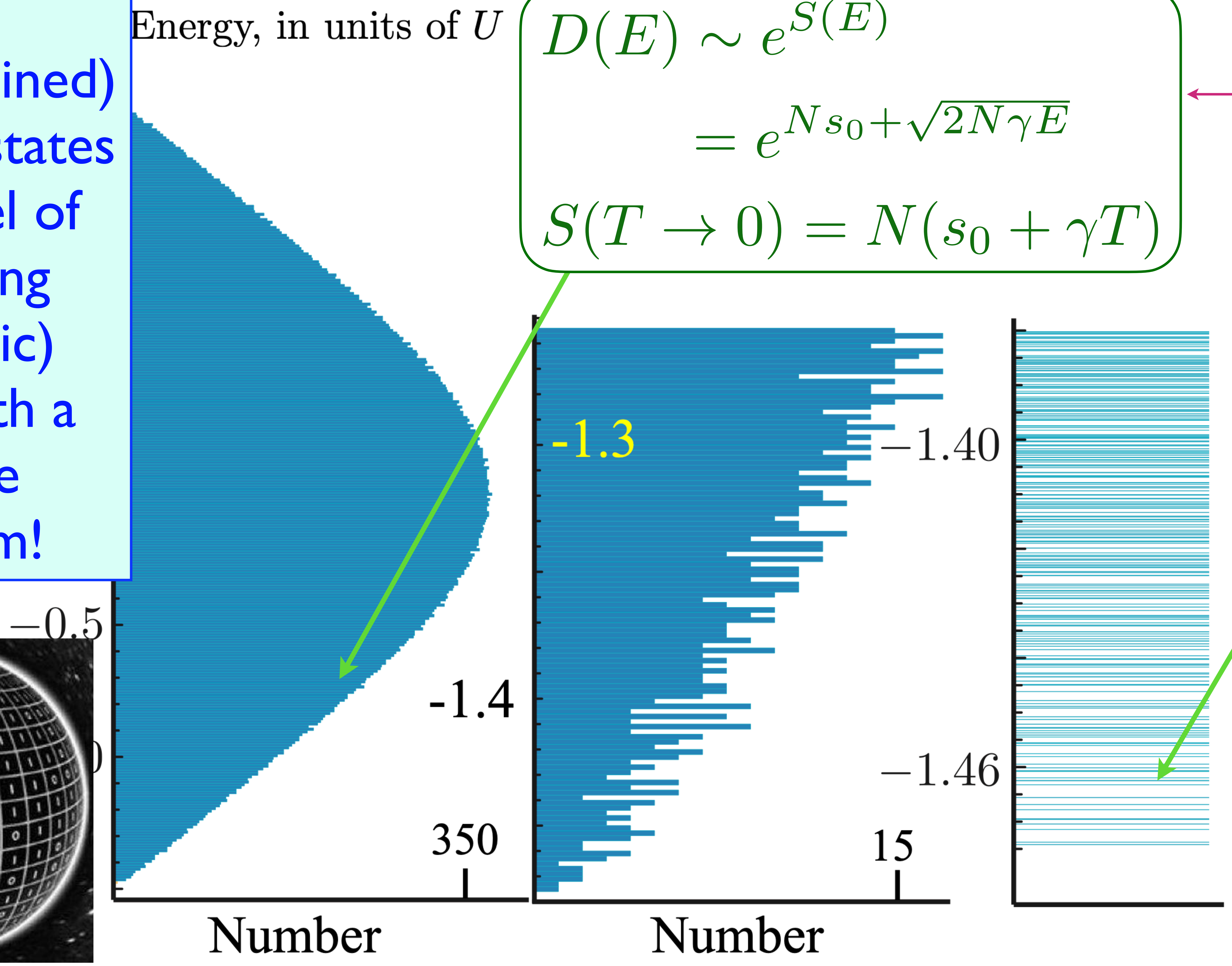
Many-body density of states

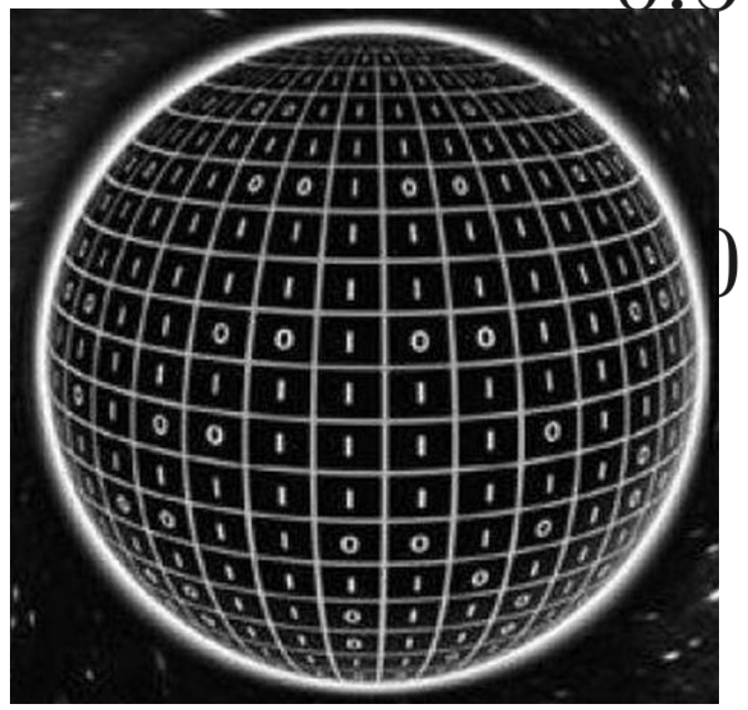
$$D(E) = \sum_i \delta(E - E_i); \quad E_0 + E_i \Rightarrow \text{Many body eigenvalue}$$

Same entropy and (coarse-grained) density of states in a model of interacting (fermionic) qubits with a discrete spectrum!

$$D(E) \sim e^{S(E)}$$
$$= e^{N s_0 + \sqrt{2N\gamma E}}$$
$$S(T \to 0) = N(s_0 + \gamma T)$$

$$D(E) \sim 2\, e^{N s_0} \sinh(\sqrt{2N\gamma E})$$
$$S(T) = N(s_0 + \gamma T) - \frac{3}{2} \ln\left(\frac{U}{T}\right)$$





$$D(E) \sim 2\, e^{N s_0} \sqrt{2N\gamma E}$$

No quasiparticle decomposition: wavefunctions change chaotically from one state to the next.

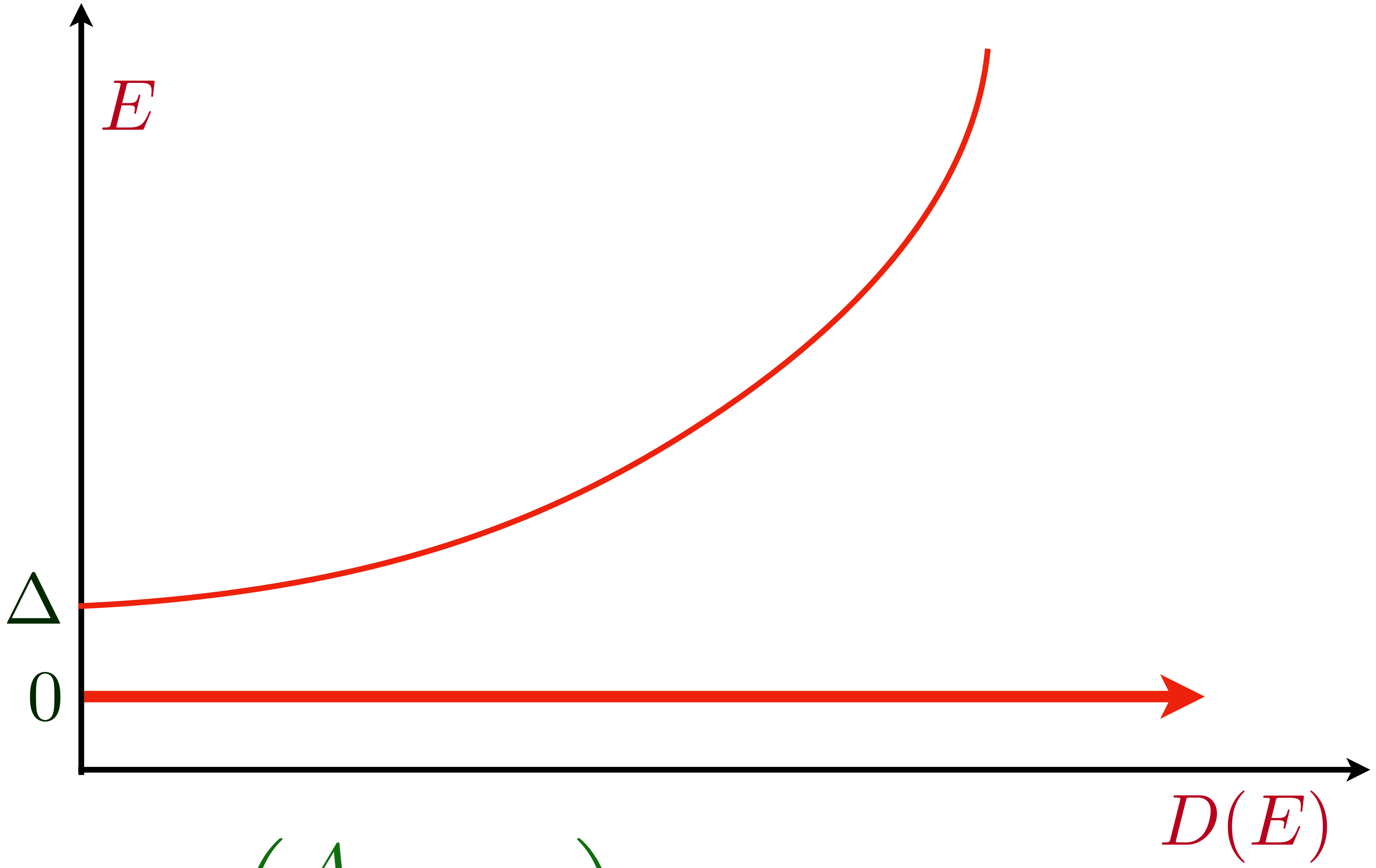
$$s_0 = 0.464848\ldots$$

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

Complex SYK model

Many-body density of states

$$D(E) = \sum_i \delta(E - E_i); \quad E_0 + E_i \Rightarrow \text{Many body eigenvalue}$$



$$D(E) \sim \exp\left(\frac{A_0}{4G} + \dots\right)\delta(E) + f_{\text{reg}}(E - \Delta), \quad \Delta \sim R_h^{-1}$$

Supersymmetric black holes and SYK models

Fu, Gaiotto, Maldacena, Sachdev (2017); Stanford, Witten (2017); Heydeman, Iliesiu, Turiaci, Zhao (2020)

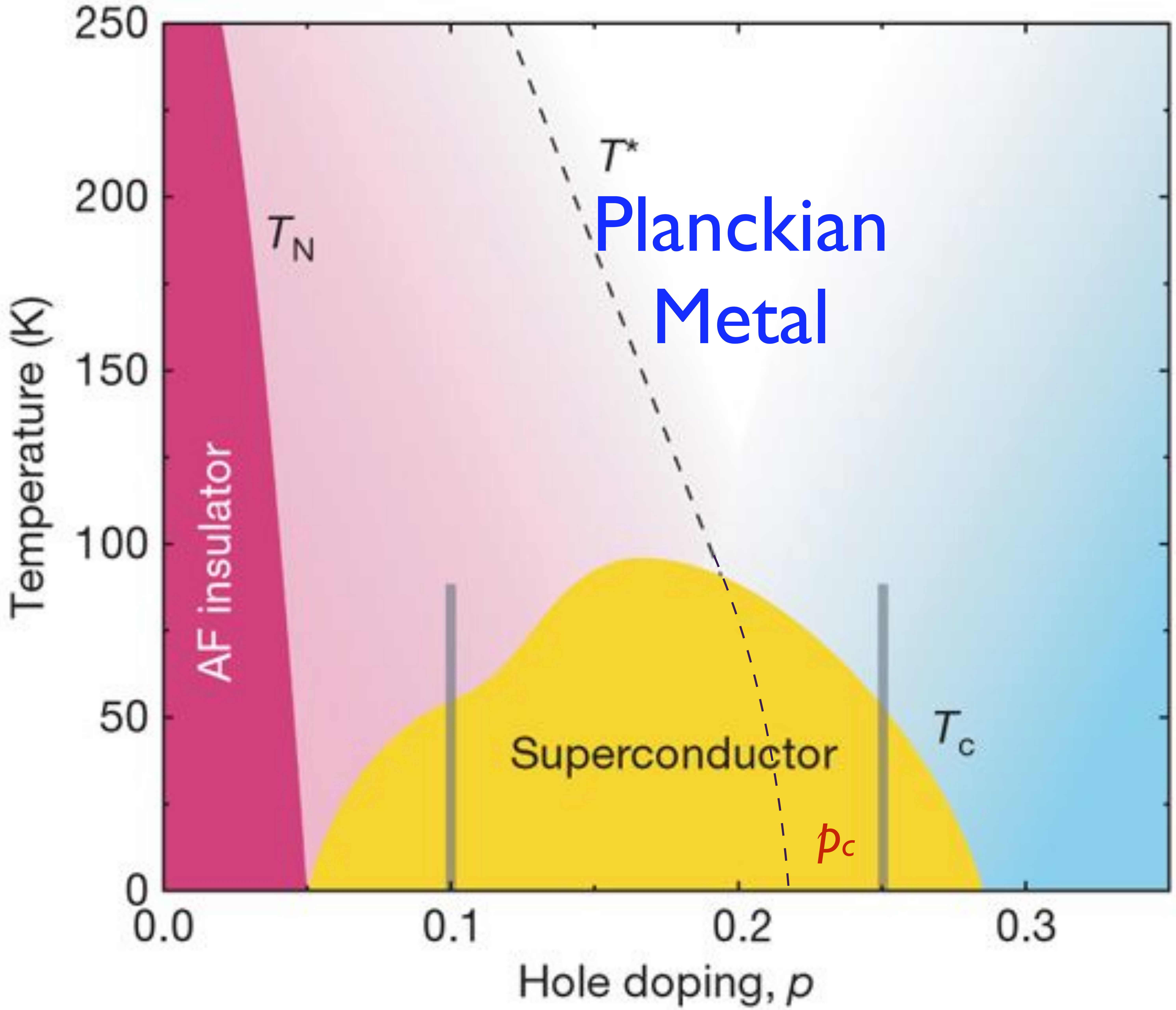
1. Introduction to Planckian metals

2. Introduction to black holes

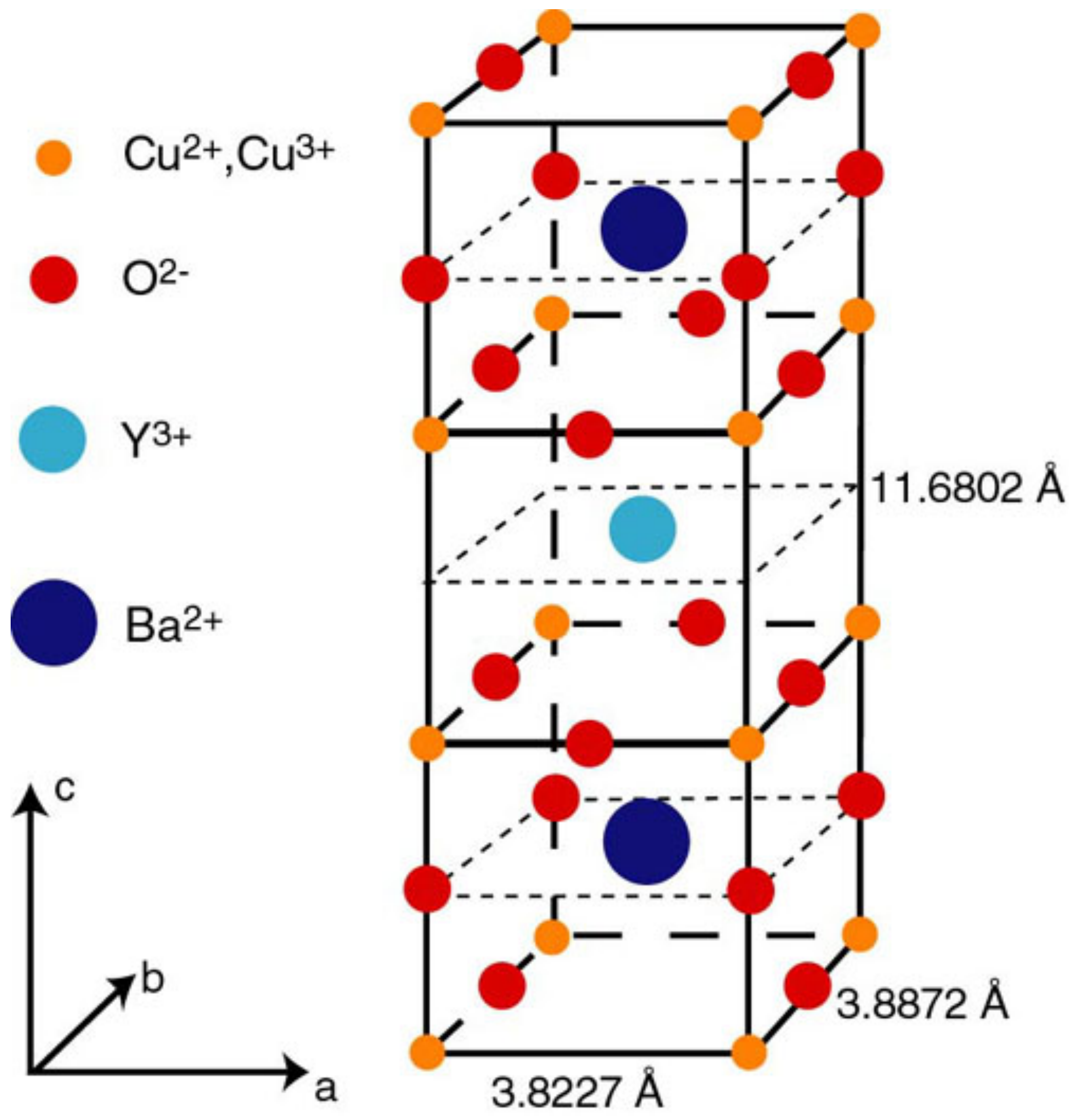
3. The SYK model

4. Progress on the theory of black holes

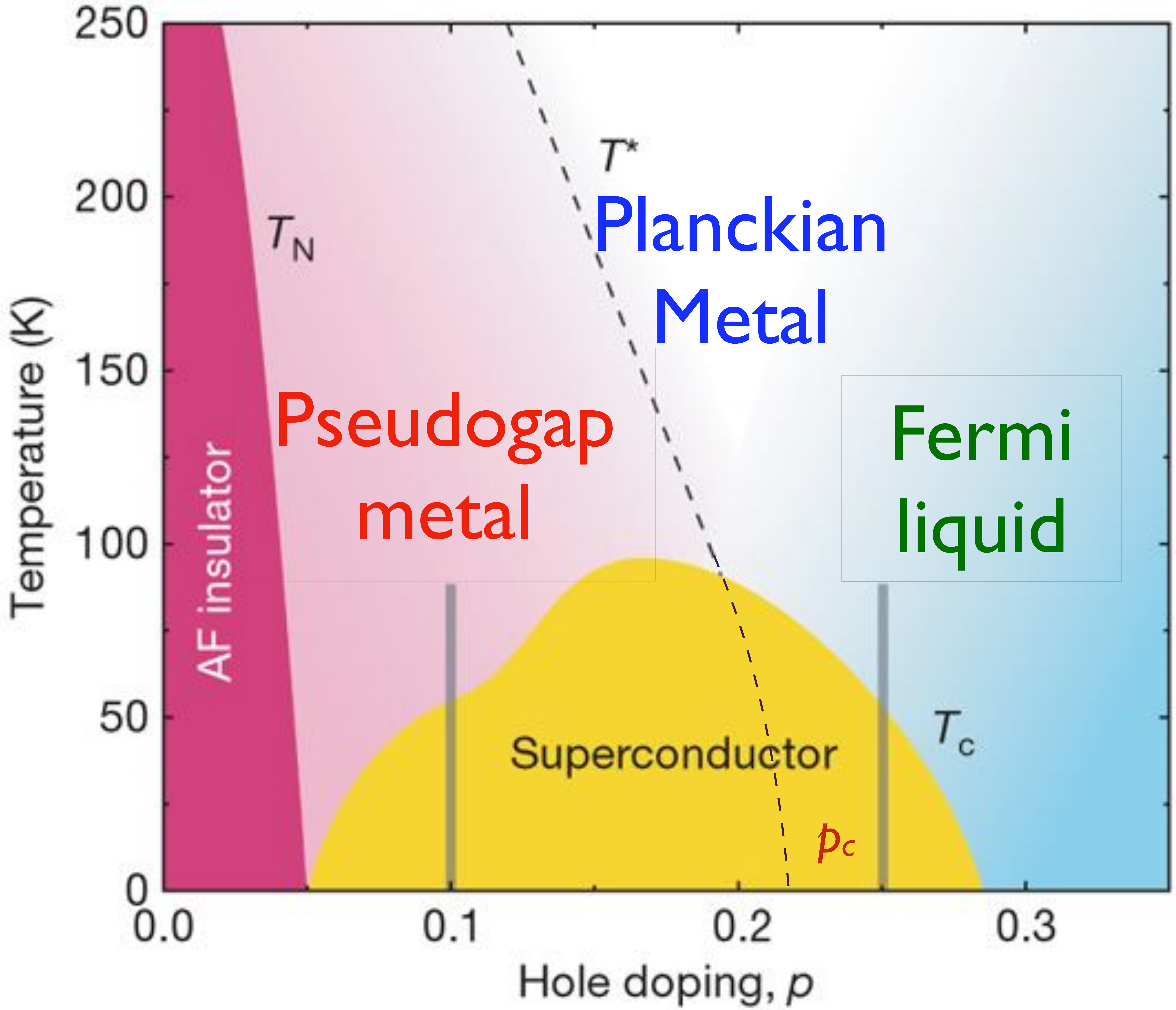
5. Progress on the theory of Planckian metals



250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Planckian
Metal
Superconductor
T_c
p_c



Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å



250
200
150
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50
0
0.0
0.1
0.2
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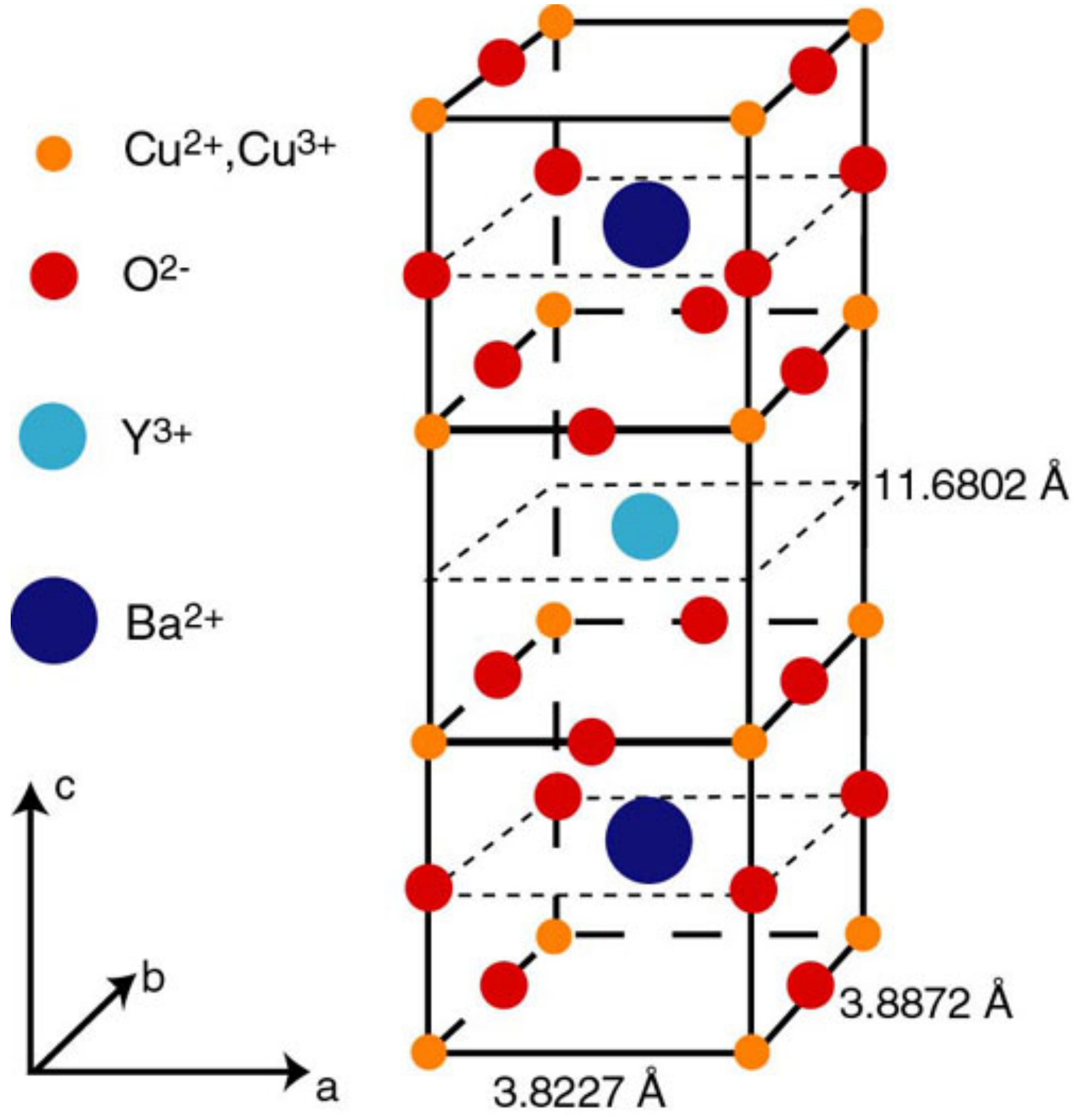
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Planckian
Metal
Pseudogap
metal
Fermi
liquid
Superconductor
T_c
p_c



Cu2+,Cu3+
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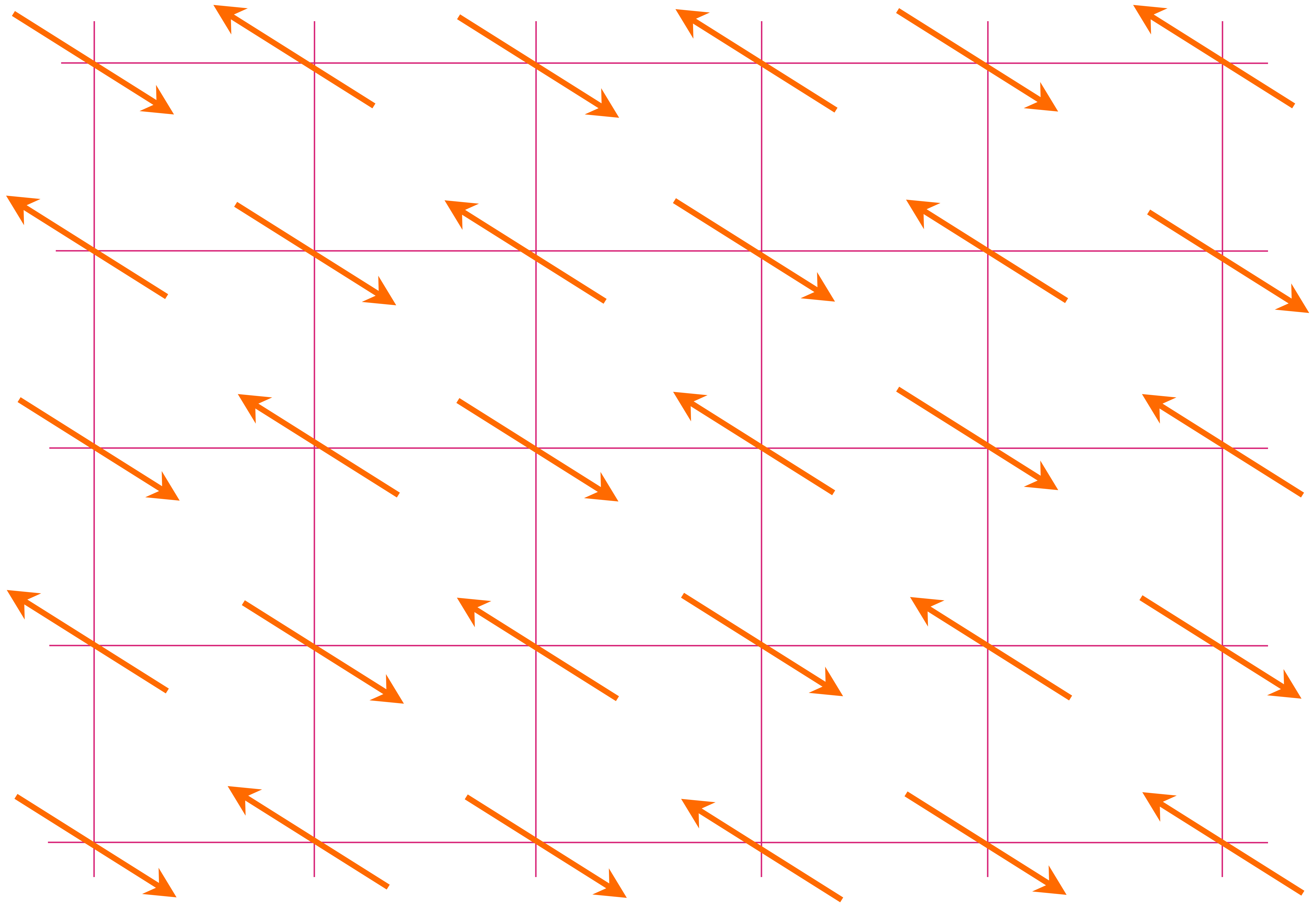
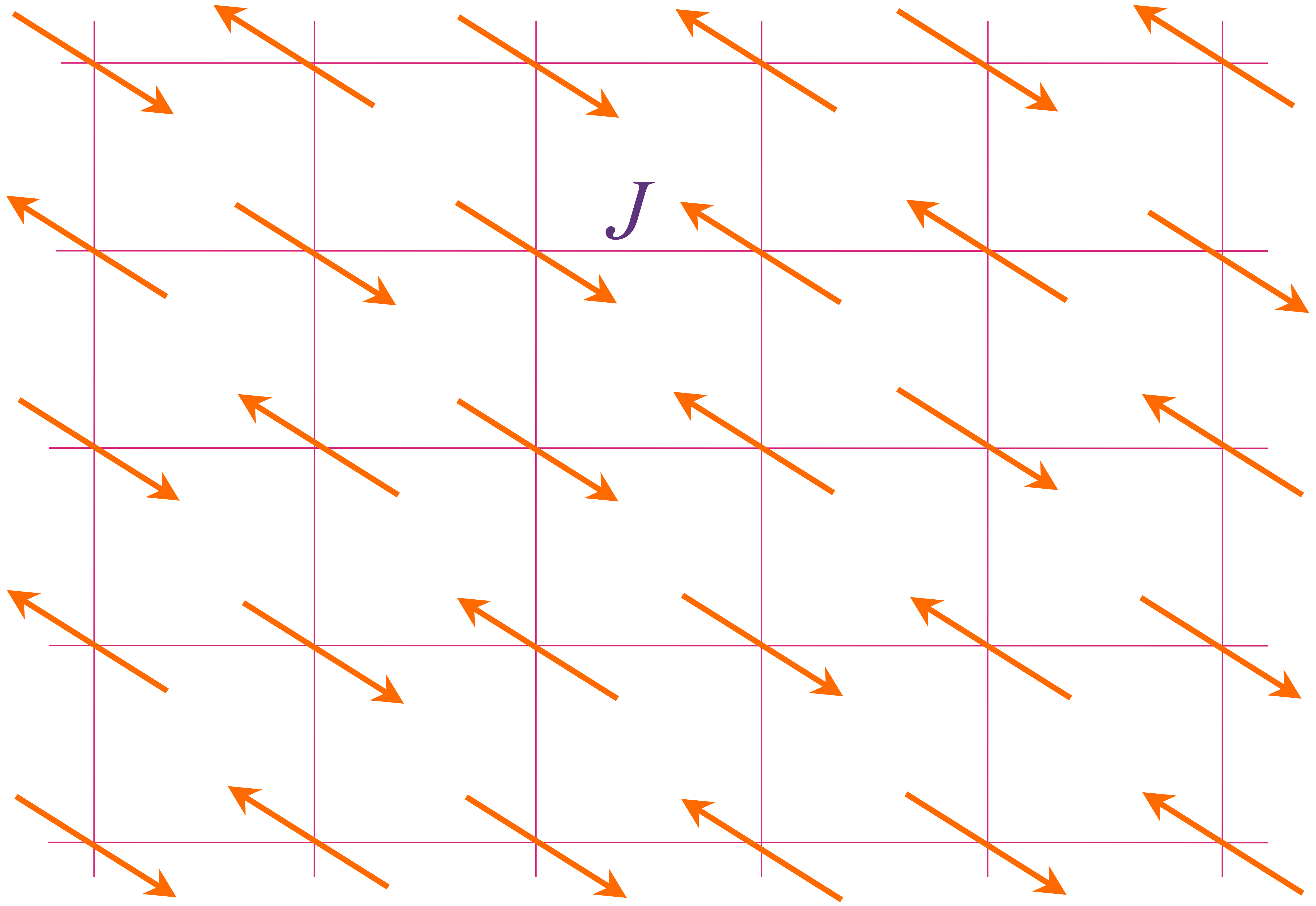
Insulating antiferromagnet



$p=0$

Insulating antiferromagnet



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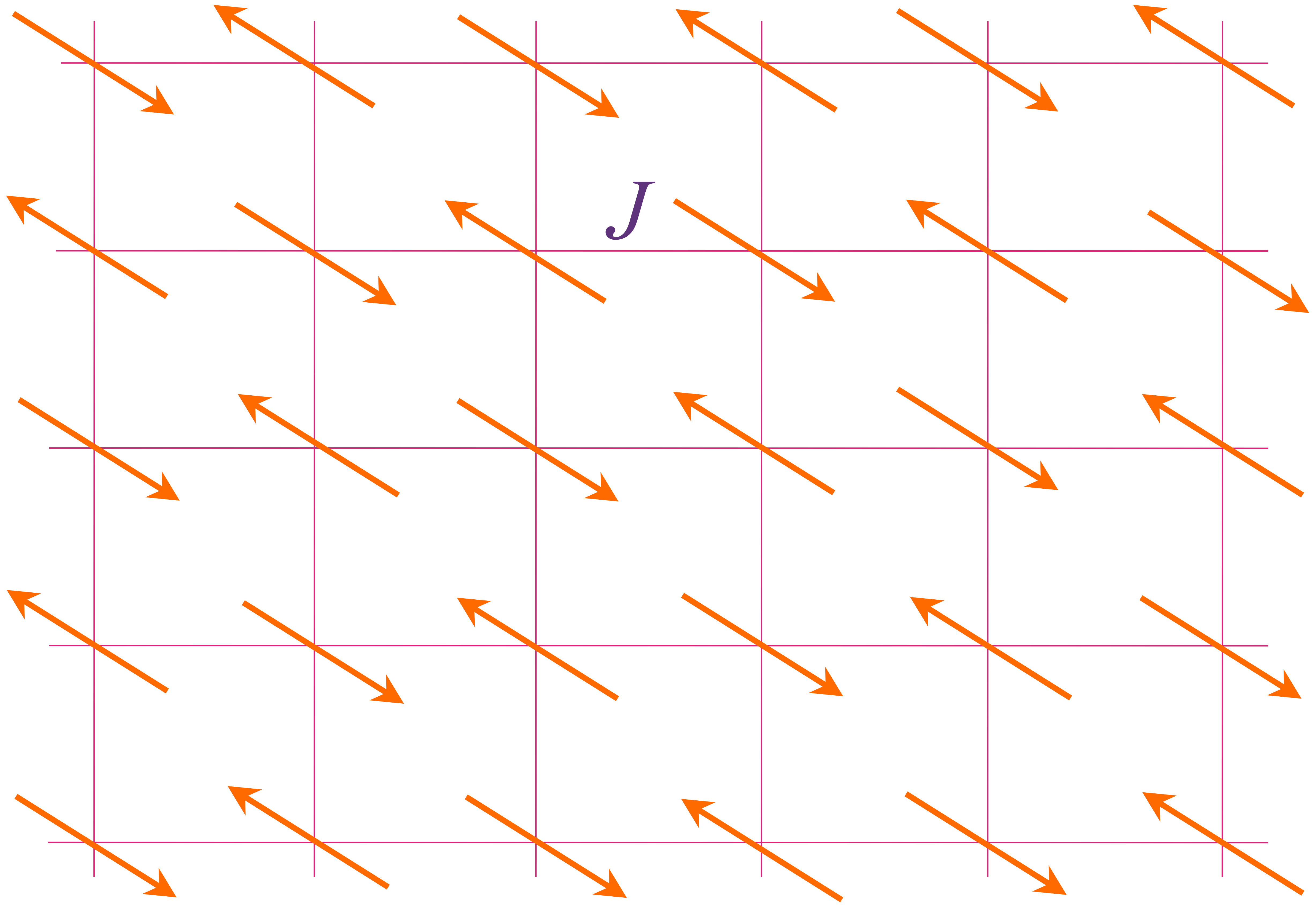
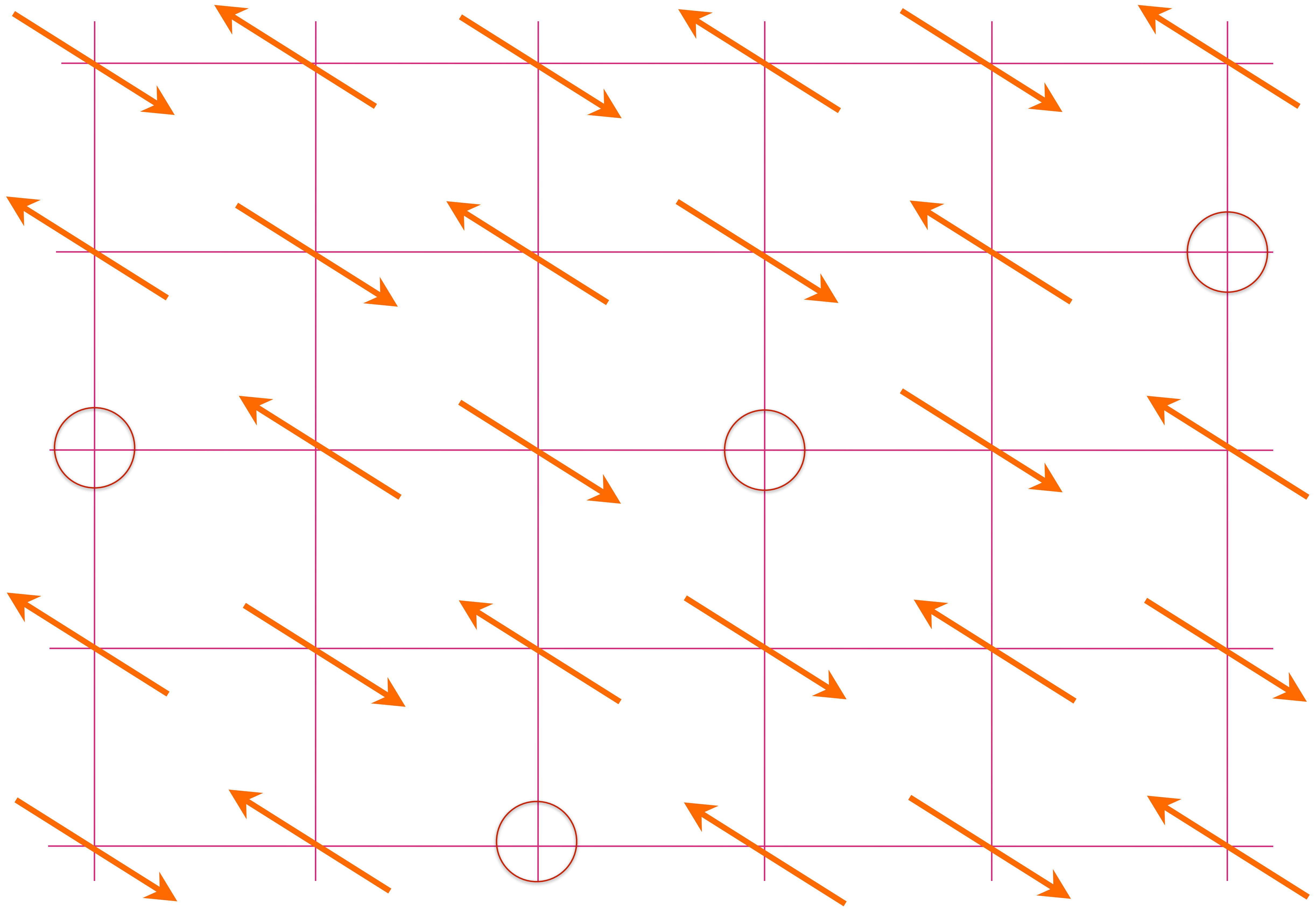


$p=0$

Antiferromagnet doped with hole density p



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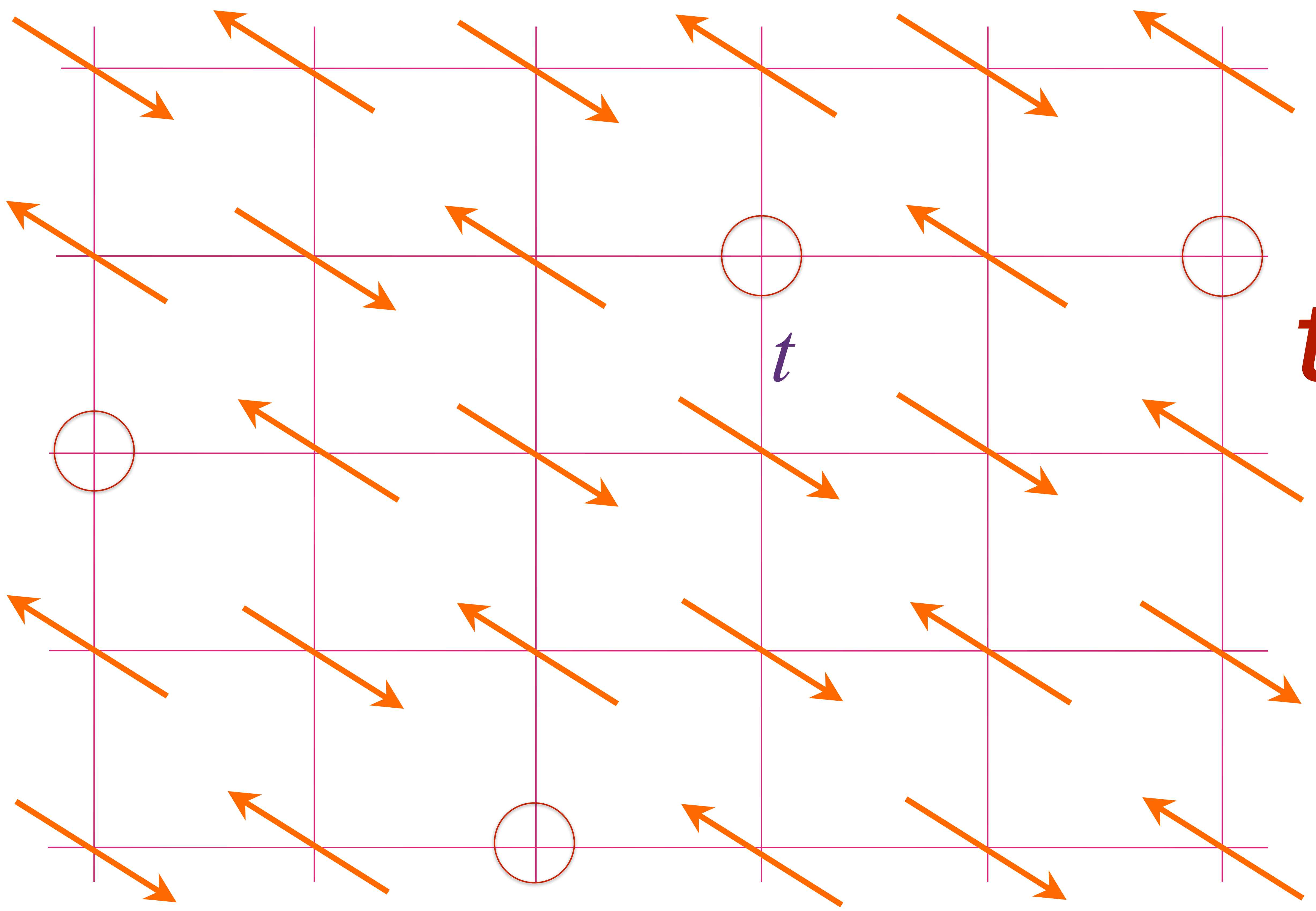
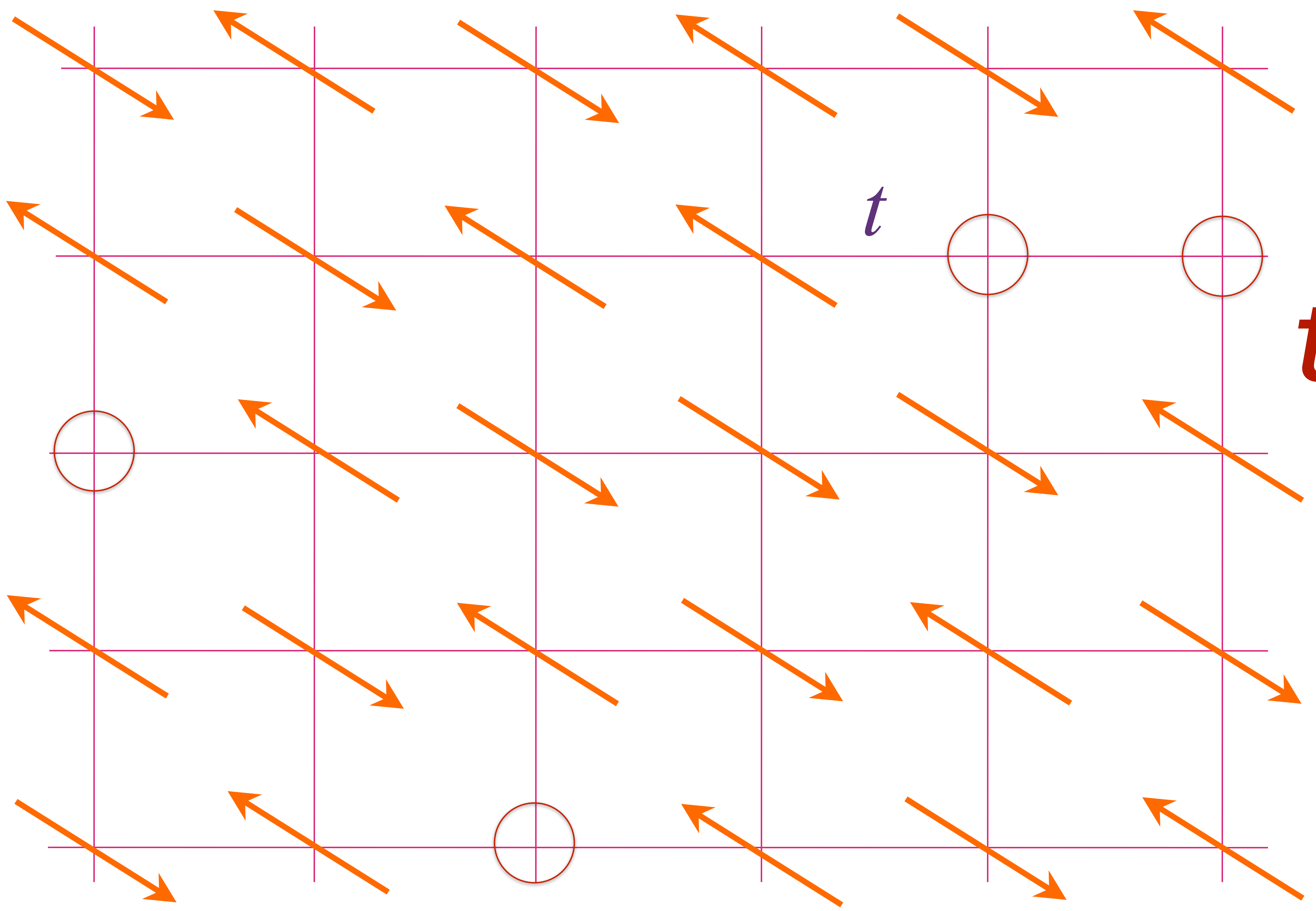


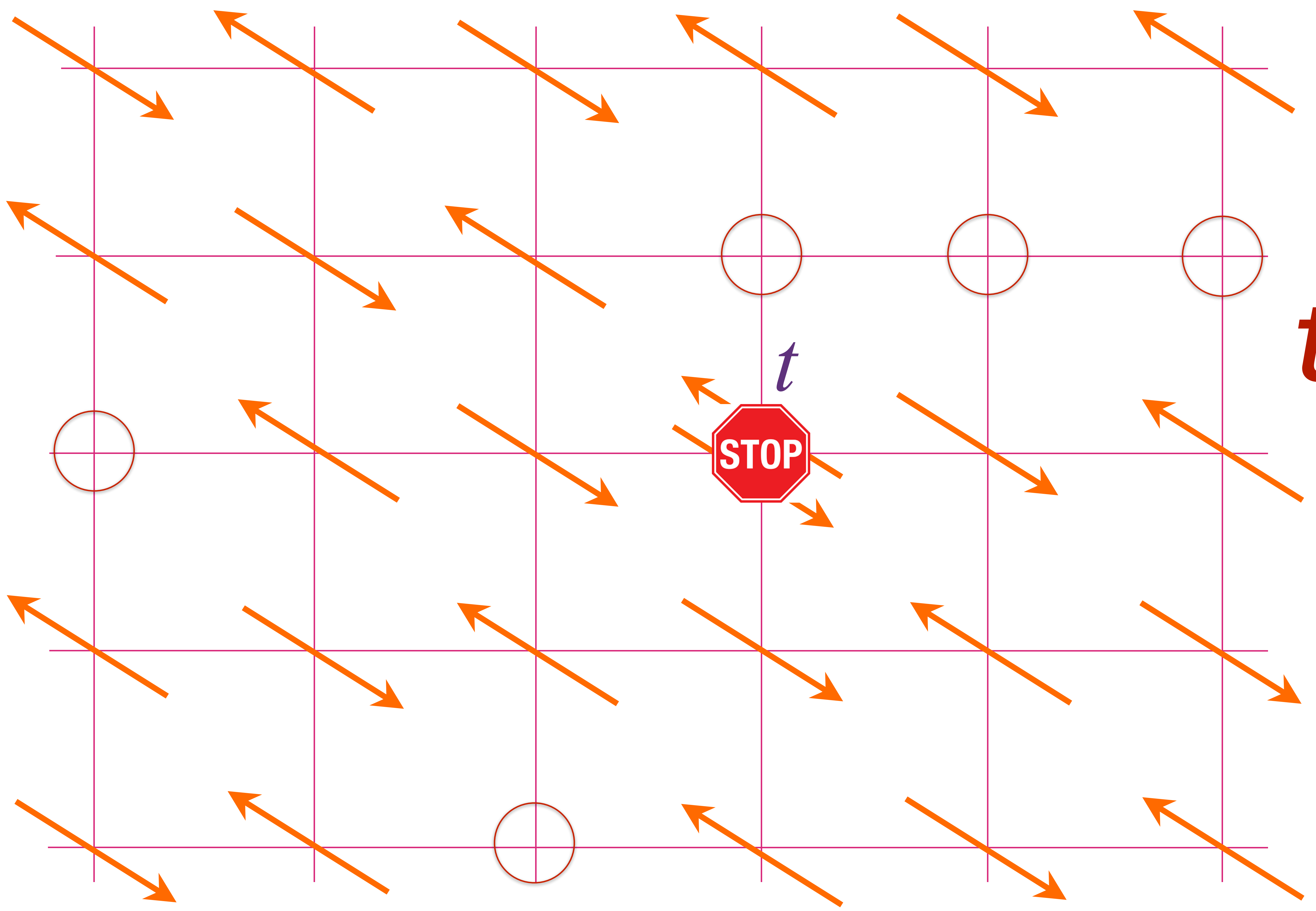
t-J model

Antiferromagnet doped with hole density p



t-*J* model

Antiferromagnet doped with hole density p



t-*J* model

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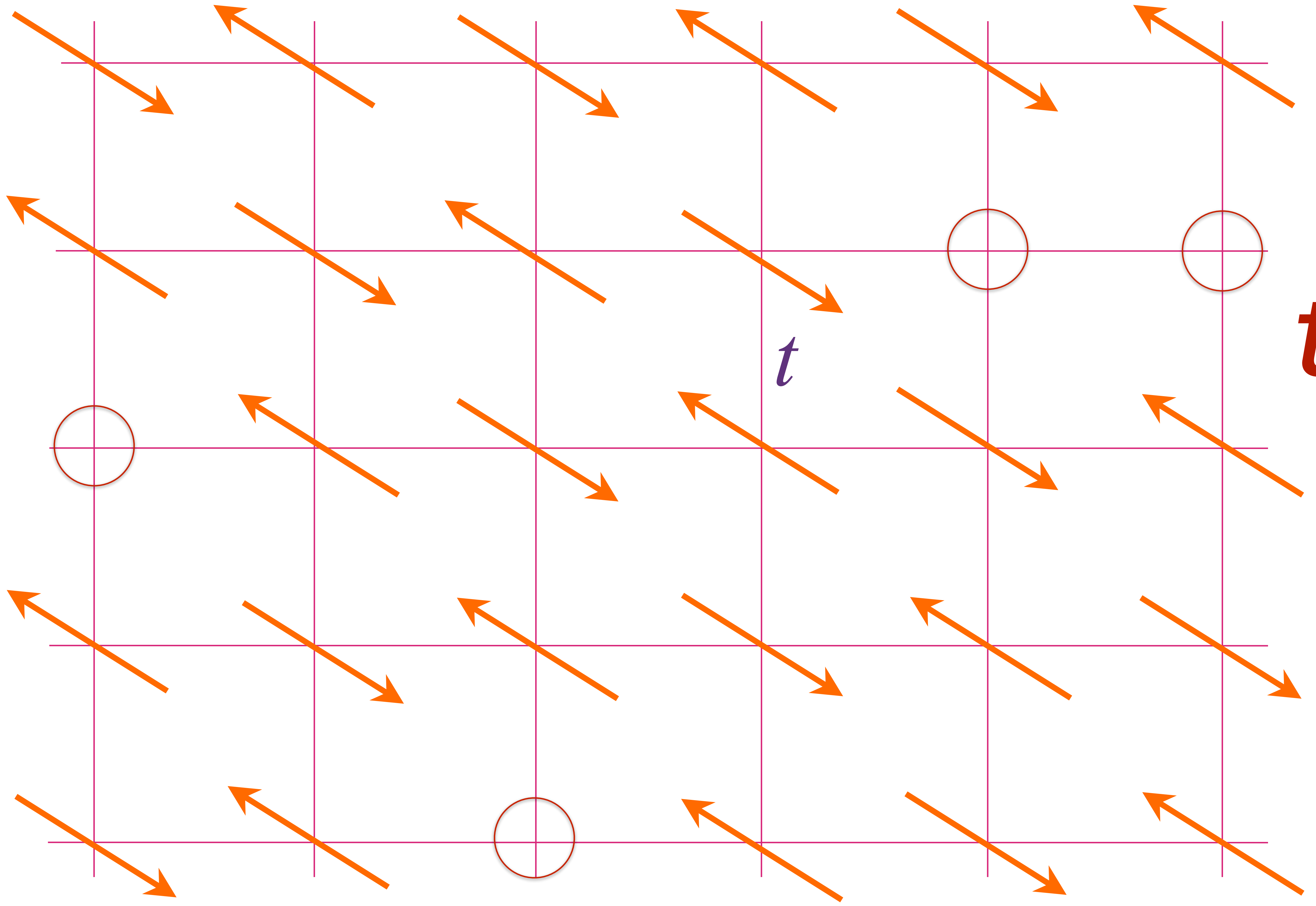

t-J model

Antiferromagnet doped with hole density p

$$H = -t \sum_{\langle ij \rangle} \mathcal{P}_d c_{i\alpha}^\dagger c_{j\alpha} \mathcal{P}_d + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

t-J model

$$\vec{S}_i = \frac{1}{2} c_{i\alpha}^\dagger \vec{\sigma} c_{i\alpha}$$

$\mathcal{P}_d$ projects out doubly-occupied sites.

D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, arXiv: 2109.05037, review article

Random *t-J* model doped with hole density p

$$H = -\frac{1}{\sqrt{N}} \sum_{i,j=1}^{N} t_{ij} \, \mathcal{P}_d c_{i\alpha}^\dagger c_{j\alpha} \mathcal{P}_d + \frac{1}{\sqrt{N}} \sum_{i<j=1}^{N} J_{ij} \, \vec{S}_i \cdot \vec{S}_j$$

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J_{ij} random, $\overline{J_{ij}} = 0$, $\overline{J_{ij}^2} = J^2$

t_{ij} random, $\overline{t_{ij}} = 0$, $\overline{t_{ij}^2} = t^2$

$J \quad \Rightarrow \quad$ two-particle interaction, as in SYK

$t \quad \Rightarrow \quad$ one-particle hopping, as in random matrices

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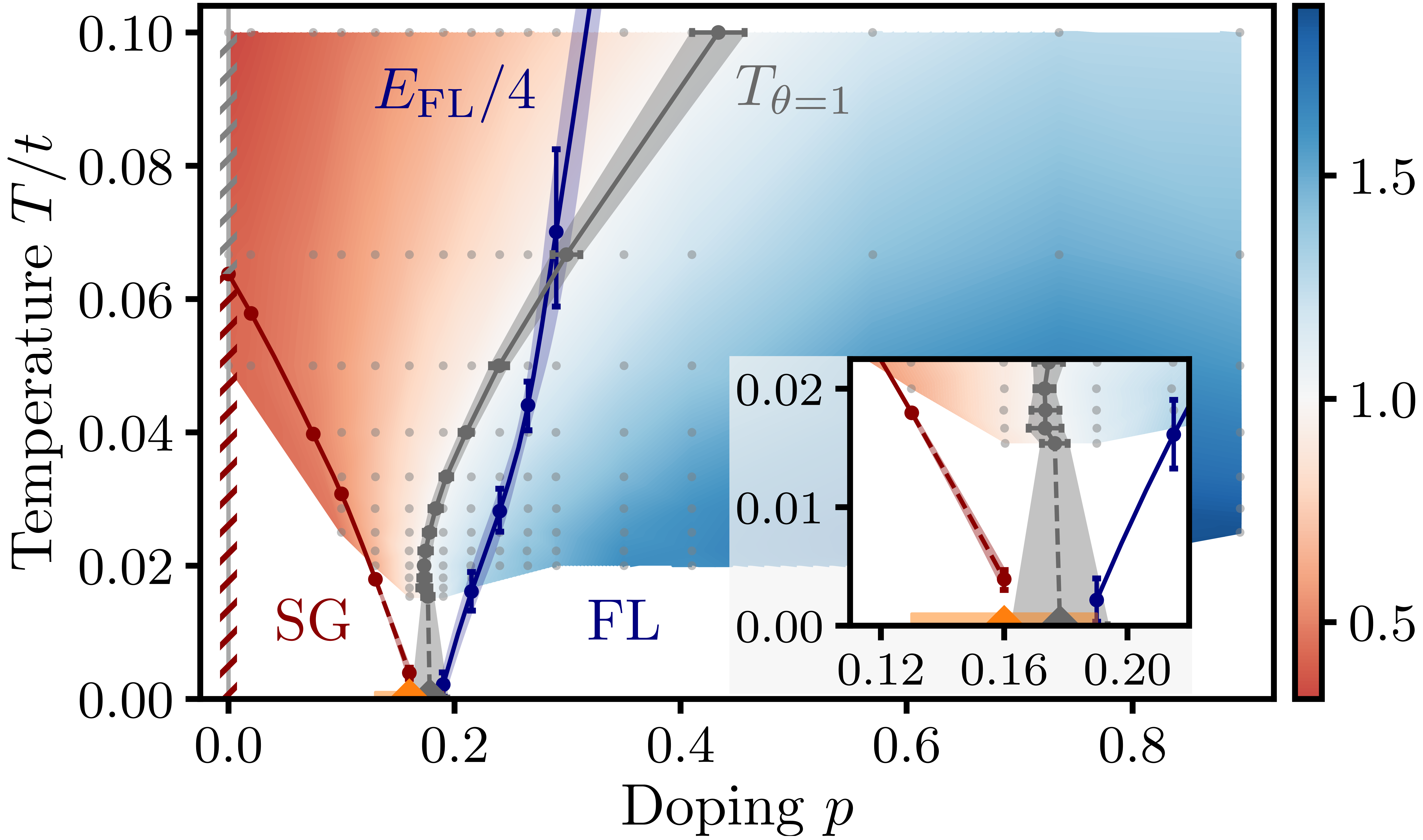
Parisi solved the model with this term only with $\vec{S}_i$ replaced by classical Ising spins $\sigma_i = \pm 1$

$J \Rightarrow$ two-particle interaction, as in SYK

$t \Rightarrow$ one-particle hopping, as in random matrices

Numerical solution of t-J model on a fully-connected cluster with all-to-all and random t_{ij} and J_{ij}



P. T. Dumitrescu, N. Wentzell, A. Georges, O. Parcollet, arXiv:2103.08607
H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)

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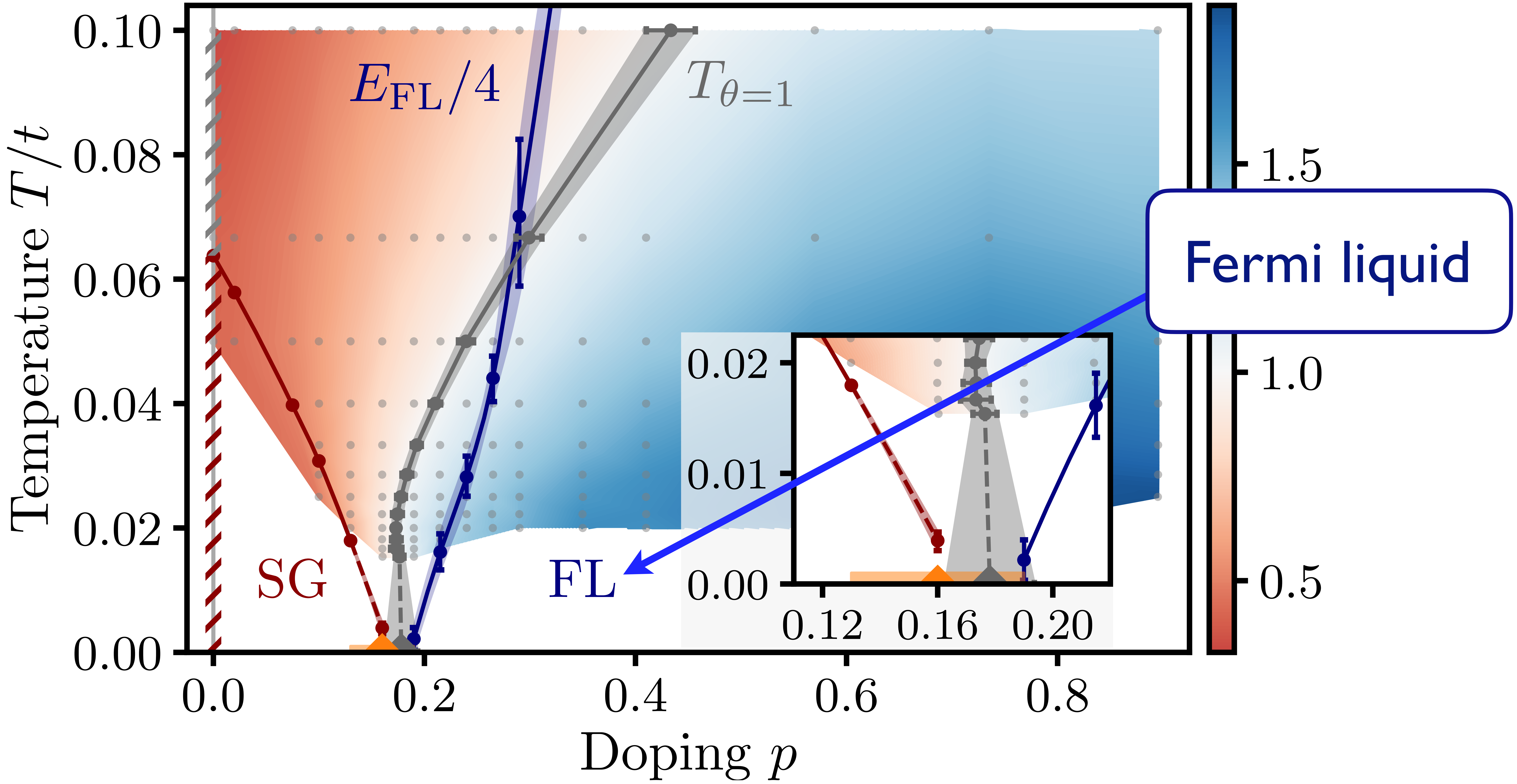

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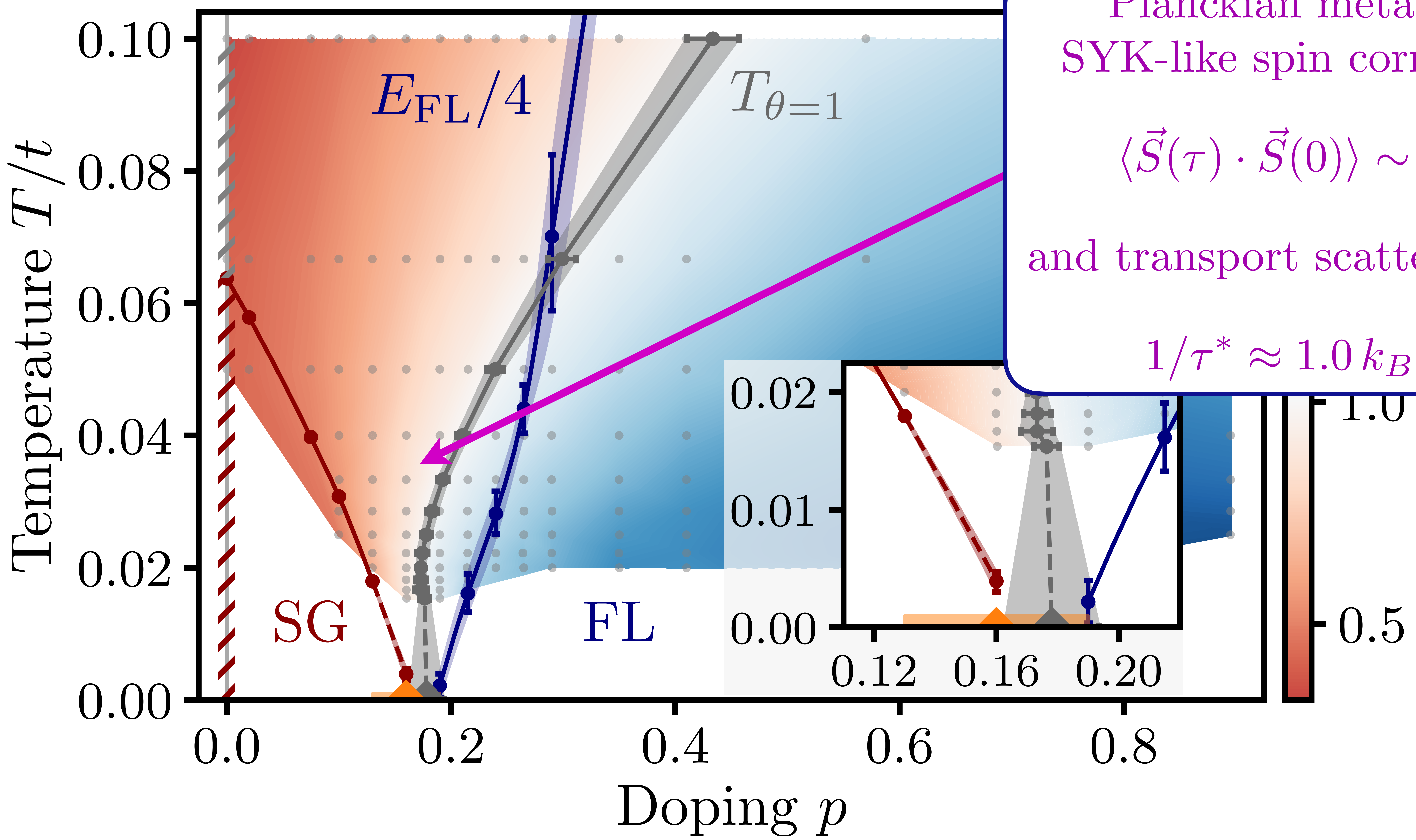


Planckian metal with SYK-like spin correlations

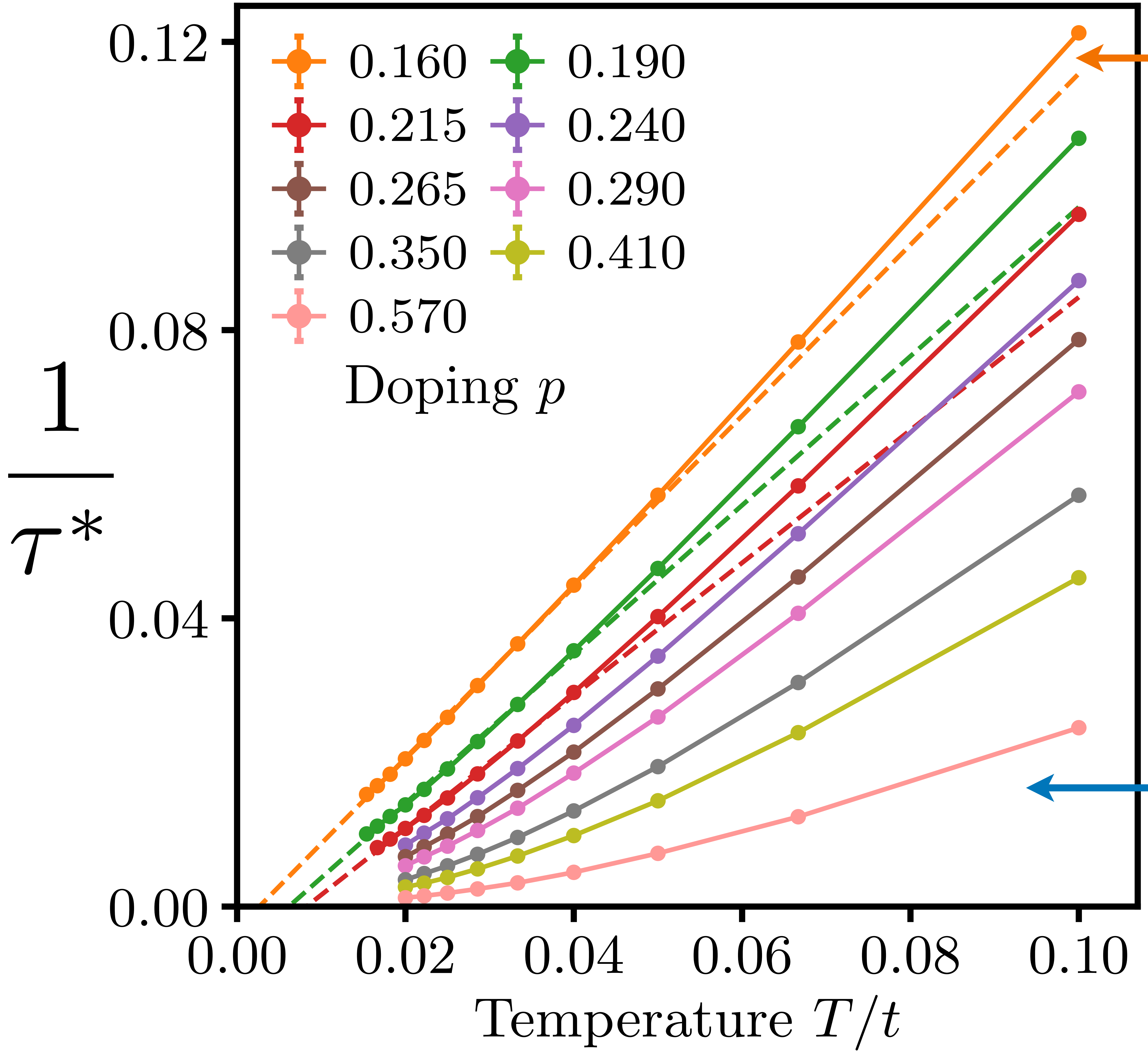
$$\langle \vec{S}(\tau) \cdot \vec{S}(0) \rangle \sim |\tau|^{-1}$$

and transport scattering time

$$1/\tau^* \approx 1.0\, k_B T/\hbar$$

P. T. Dumitrescu, N. Wentzell, A. Georges, O. Parcollet, arXiv:2103.08607

H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)



$$\frac{1}{\tau^*} \simeq c\frac{k_B T}{\hbar}$$

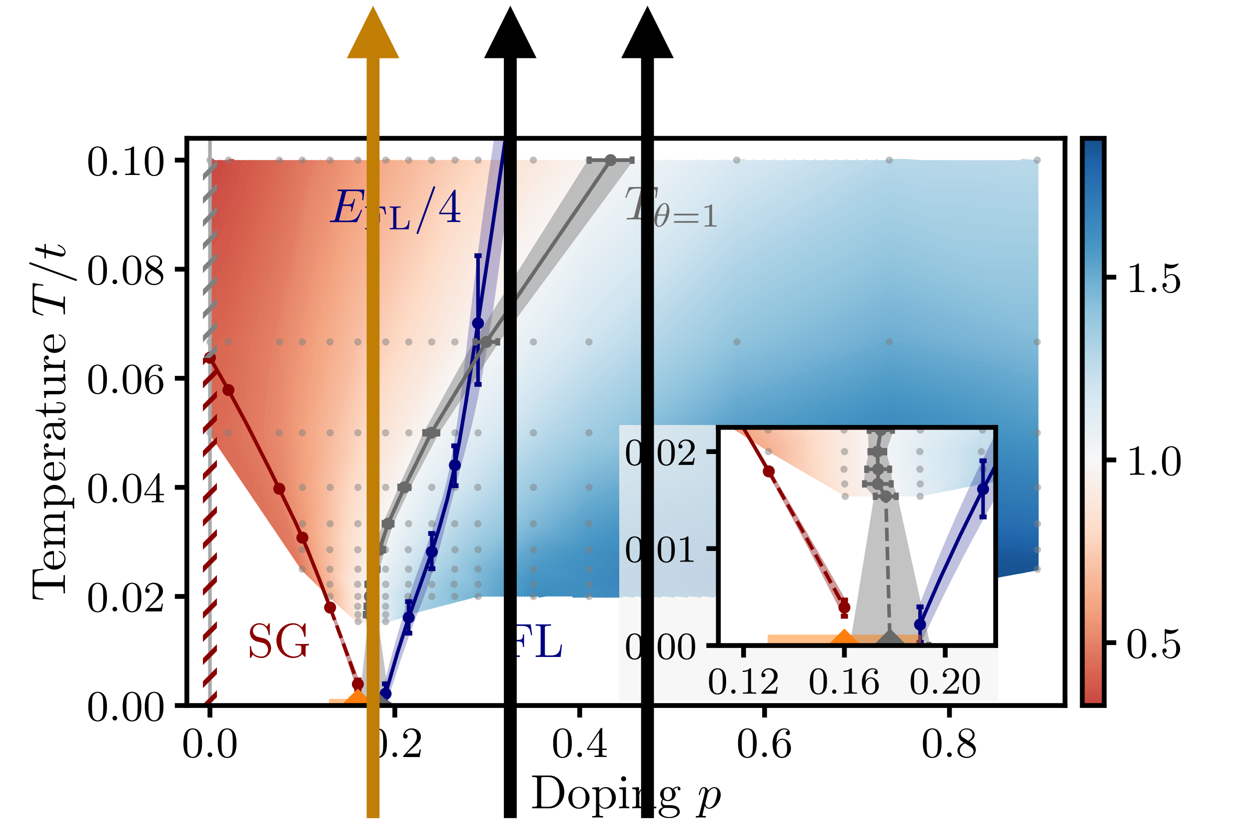
$$c \approx 1.0$$

Planckian metal
for $p \approx p_c$

Linear T resistivity
from *time reparameterization*
mode in large M theory

Haoyu Guo, Yingfei Gu, and S. Sachdev 2020

$$\frac{1}{\tau^*} \propto T^2$$



P. T. Dumitrescu, N. Wentzell, A. Georges, O. Parcollet, arXiv:2103.08607

- Why should the 2+1 dimensions t-J model be described by a 0+1 dimensional SYK-like theory over a significant temperature range ?

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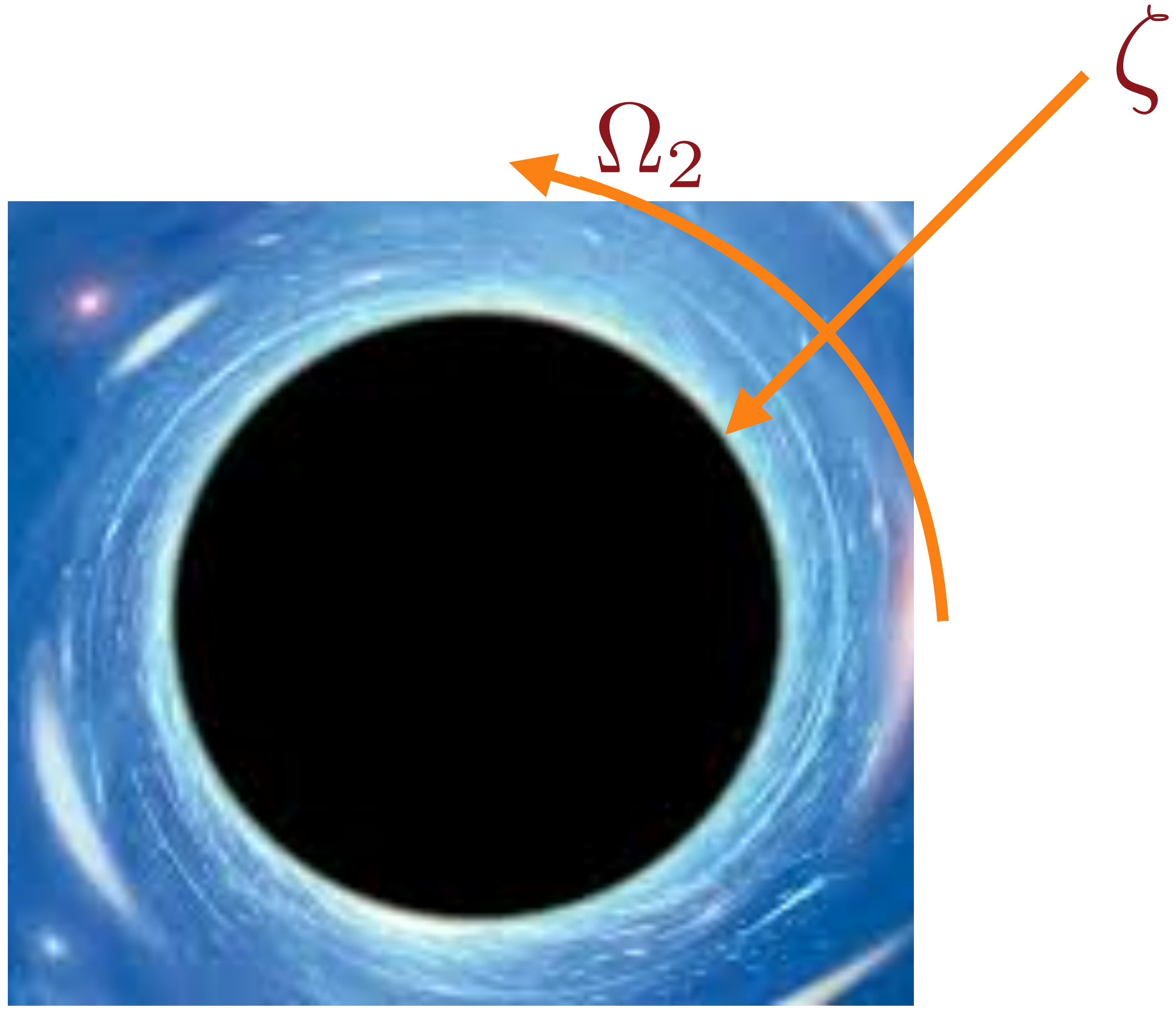
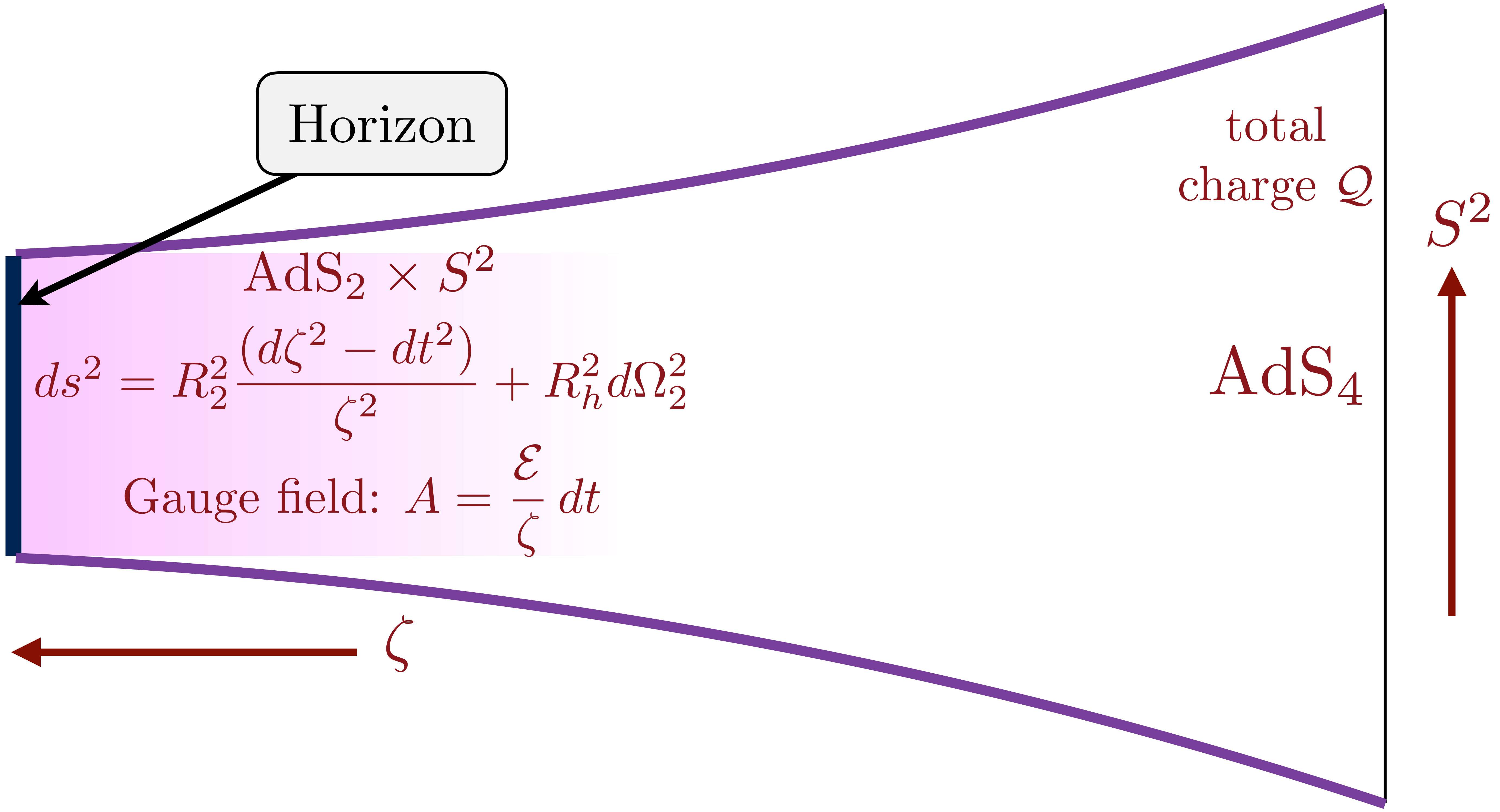
- Recall the dimensional reduction of 3+1 dimensional gravity of a charged black hole to a 1+1 dimensional theory on AdS_2 (which, in turn, describes SYK phases).





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- Recall the dimensional reduction of 3+1 dimensional gravity of a charged black hole to a 1+1 dimensional theory on AdS_2 (which, in turn, describes SYK phases).
- By the holographic mapping, this implies that certain models of Fermi surfaces coupled to large N gauge fields in 2+1 dimensions display a dimensional reduction to a 0+1 dimensional theory.

Tom Faulkner, Nabil Iqbal, Hong Liu, John McGreevy, Mark Mezei, David Vegh, 2011
D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, arXiv: 2109.05037

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- By the holographic mapping, this implies that certain models of Fermi surfaces coupled to large N gauge fields in 2+1 dimensions display a dimensional reduction to a 0+1 dimensional theory.

- The transition between the pseudogap and the Fermi liquid in the t-J model can be written as $SU(2) \times U(1)$ gauge theory.

Ya-Hui Zhang, S. Sachdev, A Nikolaenko, M. Tikhanovskaya 2020,2021
D. Chowdhury, Liujun Zou 2020

Summary

- SYK: a solvable model without quasiparticle excitations, exhibiting thermalization and many-body chaos in a time of order $\hbar/(k_B T)$, independent of microscopic energy scales.

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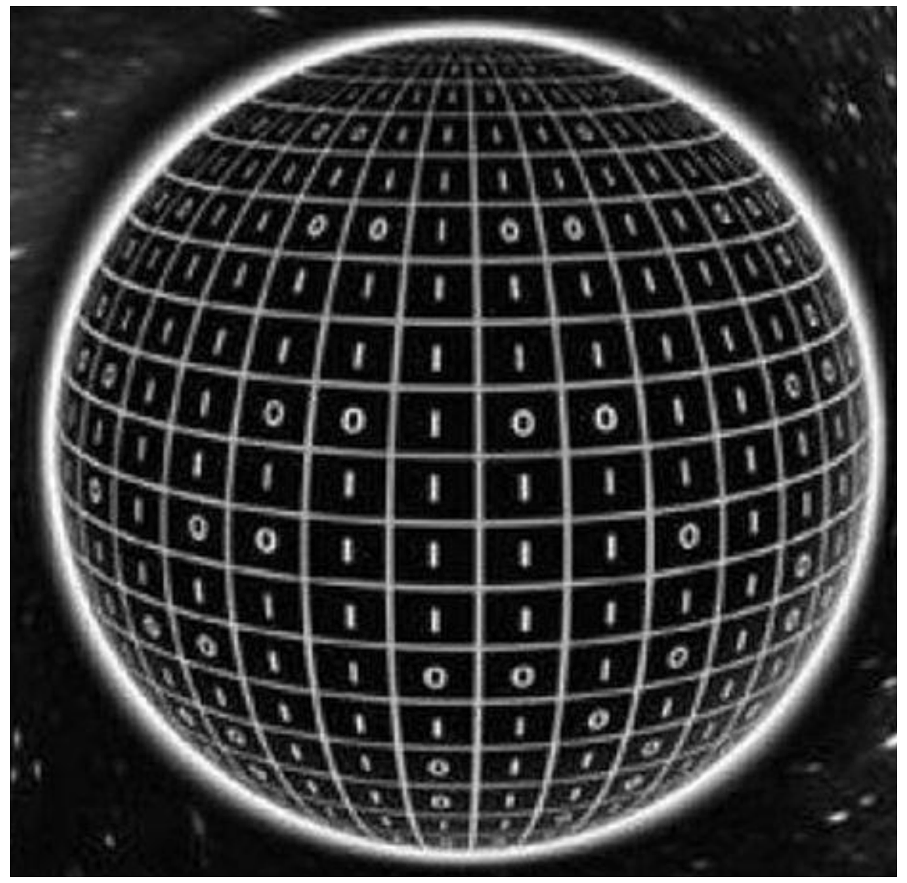
- SYK: a solvable model without quasiparticle excitations, exhibiting thermalization and many-body chaos in a time of order $\hbar/(k_B T)$, independent of microscopic energy scales.

- Low energy theory of time reparameterizations is the theory of the boundary graviton in 2D quantum gravity on AdS_2.

Summary

- Boundary graviton leads to universal $-3/2\ln(1/T)$ correction to Bekenstein-Hawking entropy of low T charged black holes in Einstein gravity, and to the SYK model. So the semiclassical entropy of Einstein gravity is reproduced by a unitary quantum system with a discrete spectrum. Further work along these lines has led to progress on the Page curve describing the time evolution of the entropy of an evaporating black hole.



Summary

- SYK-like random t-J model captures many aspects of the cuprates over a wide intermediate temperature range, including the Planckian metal behavior.