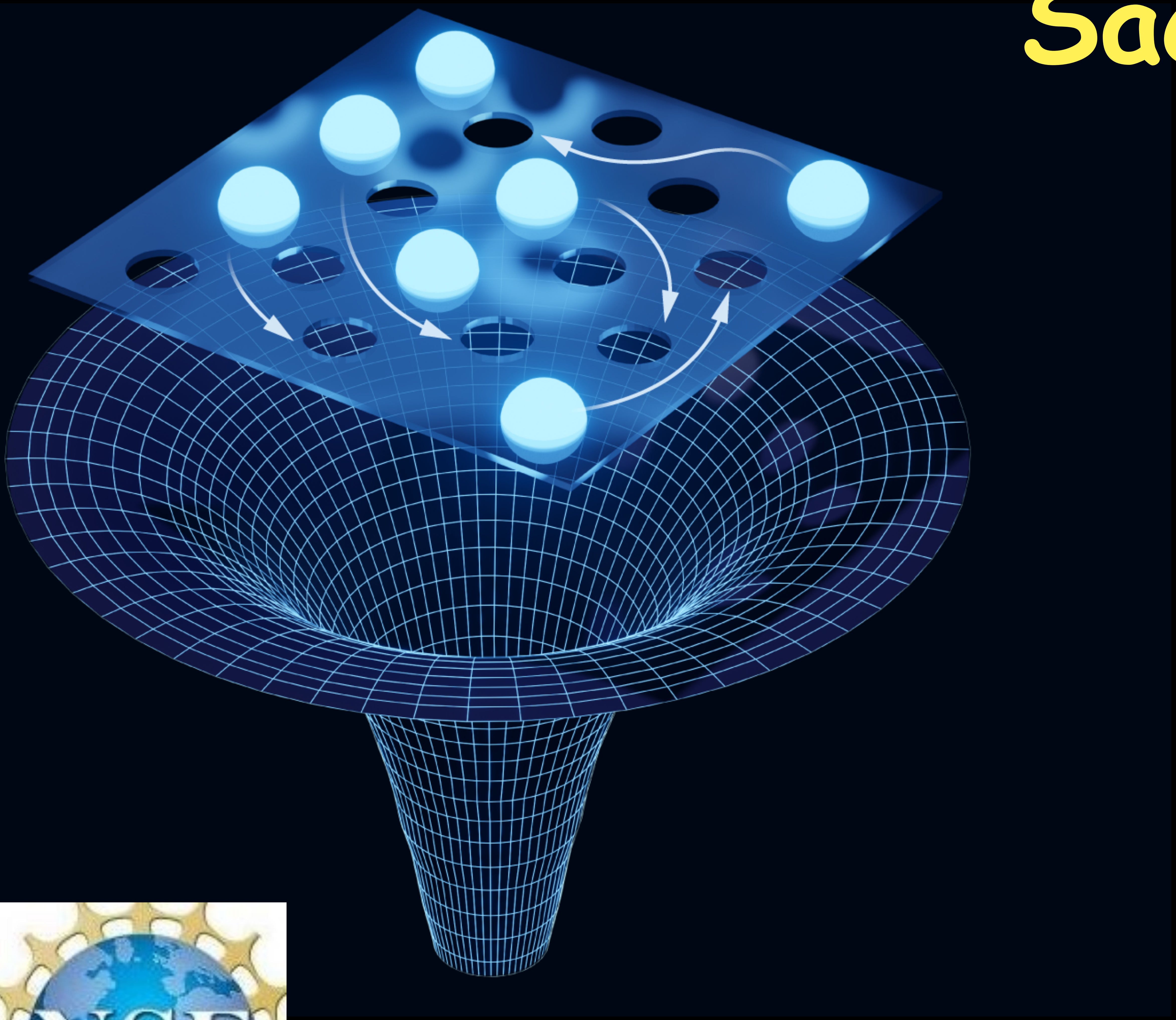
From the Sachdev-Ye-Kitaev model to theories of strange metals and black holes



Spotlight Lecture, Shaastra 2025
Indian Institute of Technology, Madras
January 6, 2025

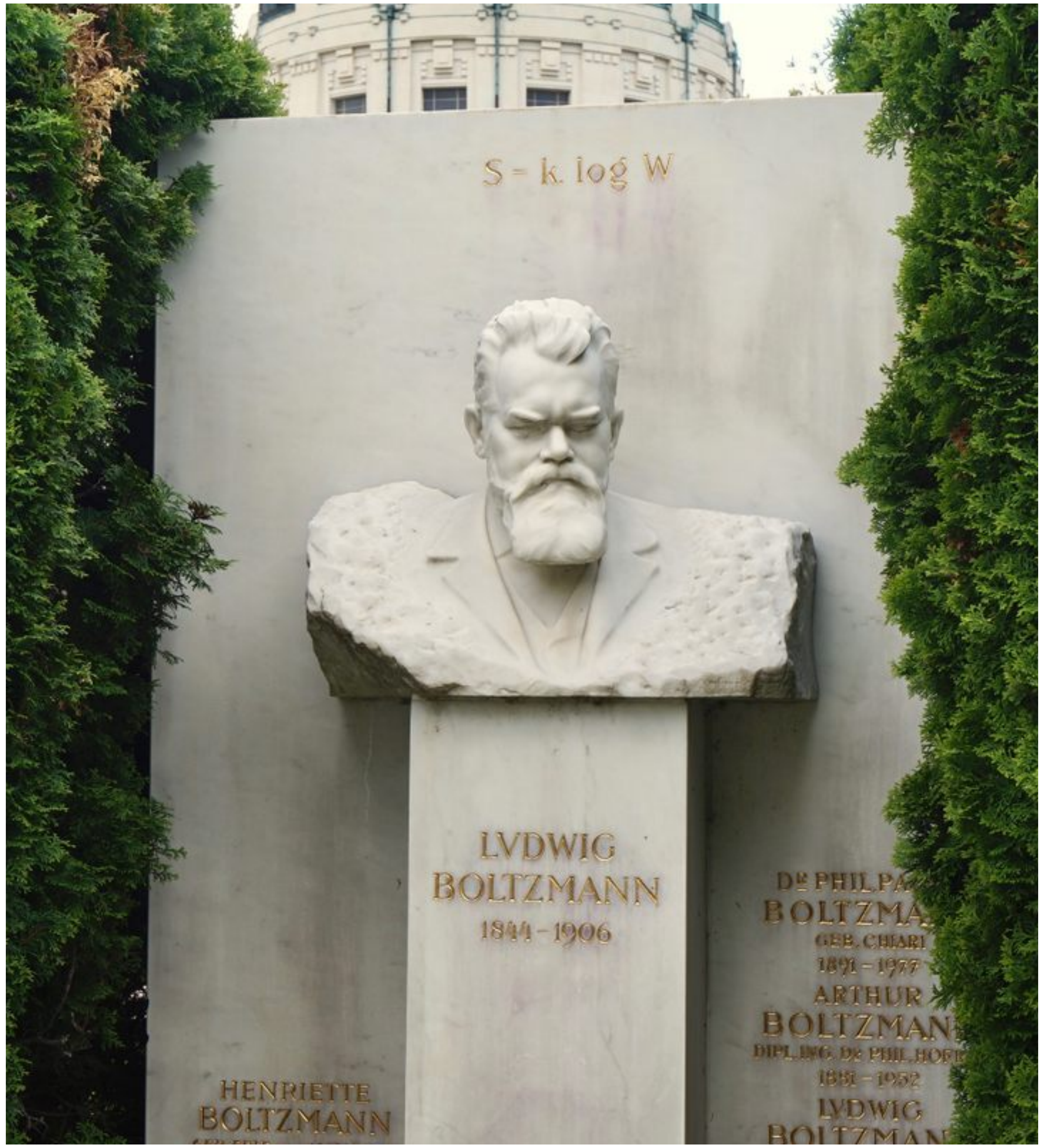
Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

Boltzmann-Landau theory of ordinary metals: Cu, Ag

Statistical interpretation of entropy (1870)

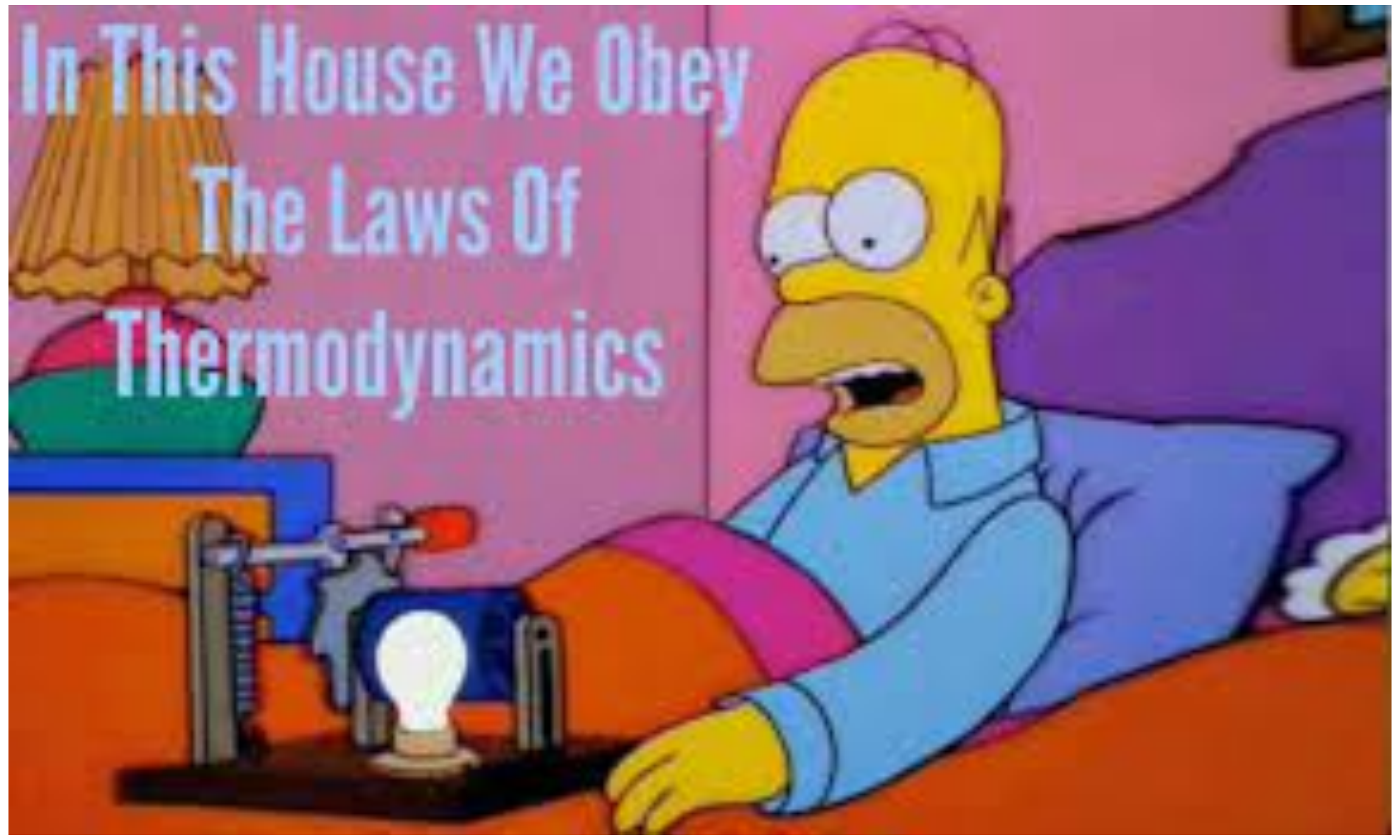


Ludwig Boltzmann
20 February 1844 - September 5, 1906
Vienna, Austria

$$S = k_B \log W$$

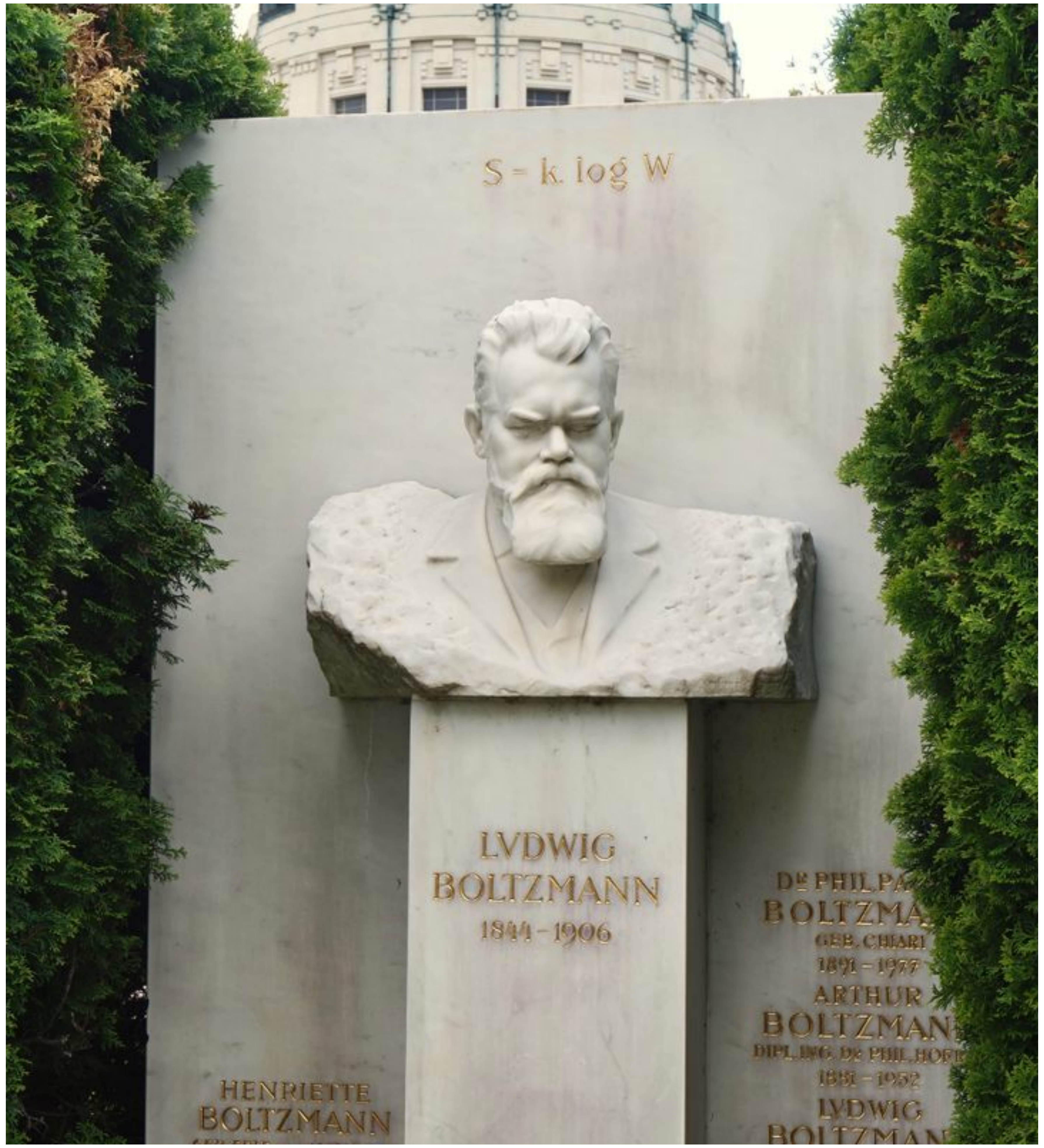
Density of quantum states $D(E) = \exp(S(E)/k_B)$

$$\frac{1}{T} = \frac{dS}{dE}$$



No perpetual motion machines!

Boltzmann equation (1872)
Dilute classical gas



Ludwig Boltzmann
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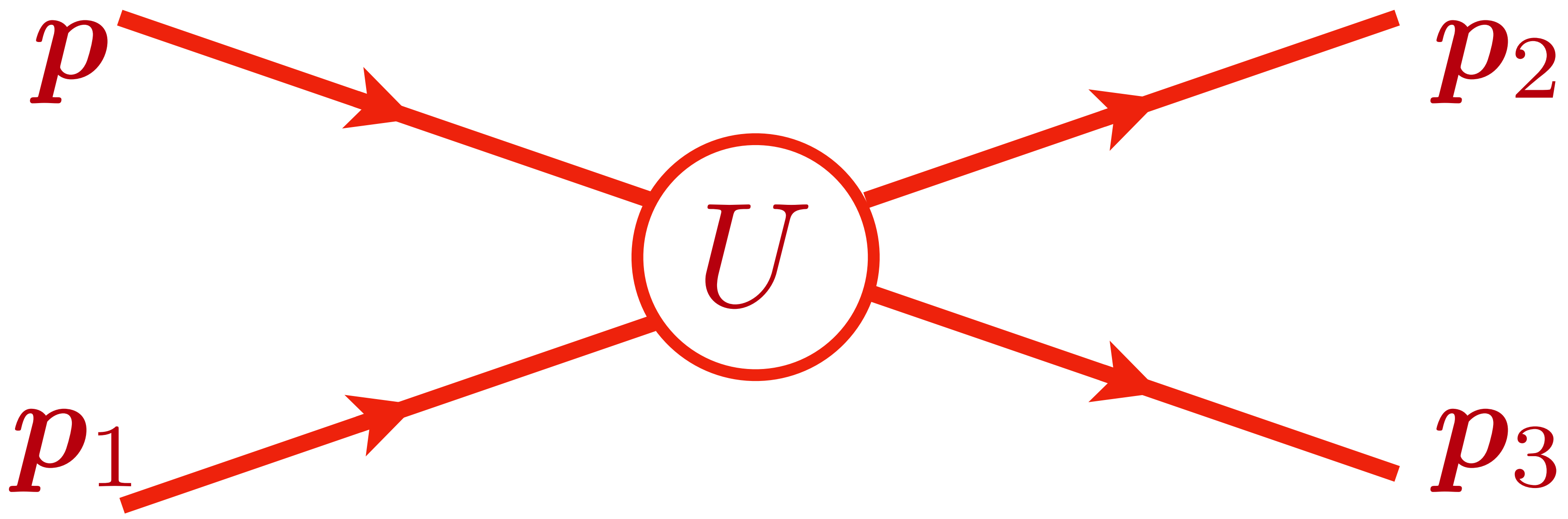
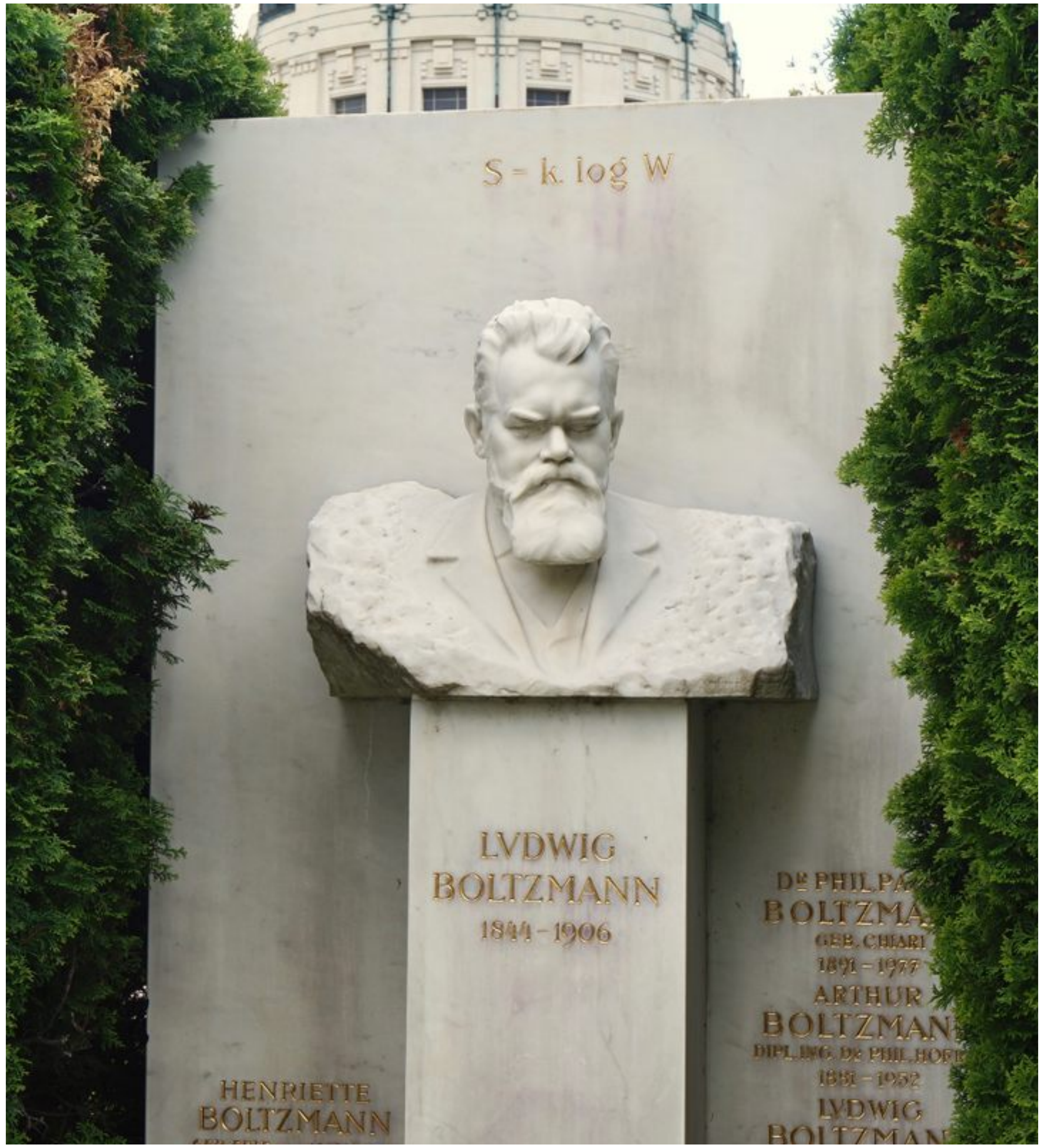
Molecular chaos:
successive collisions are rare and statistically independent





Ludwig Boltzmann
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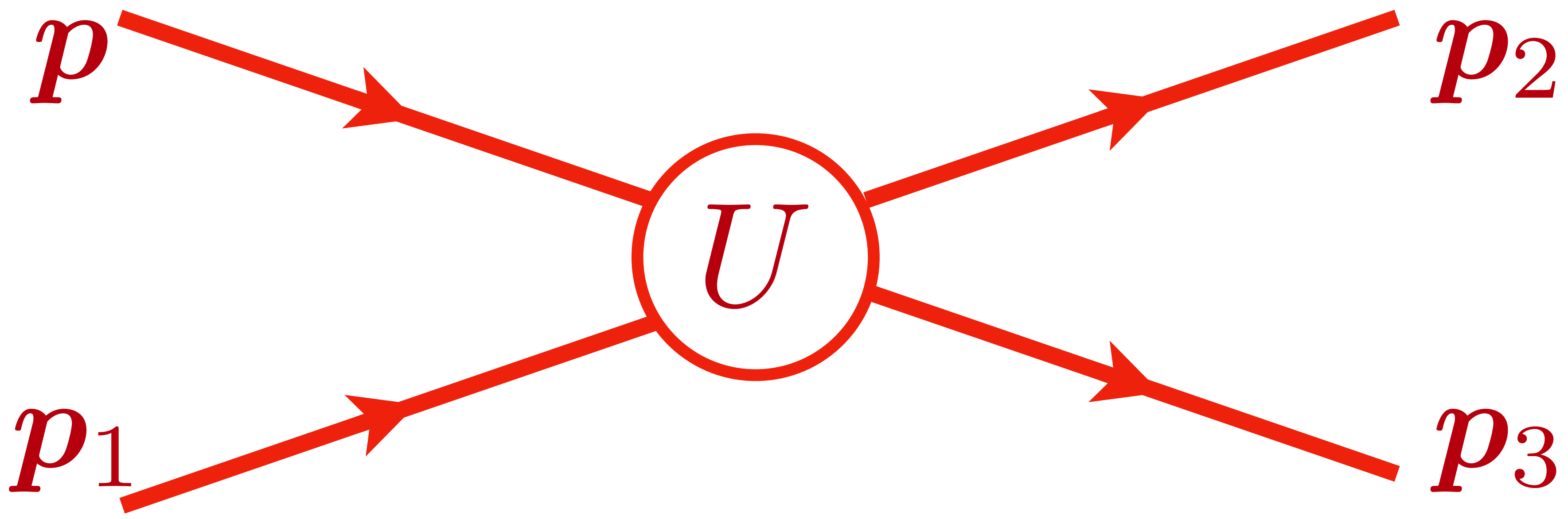
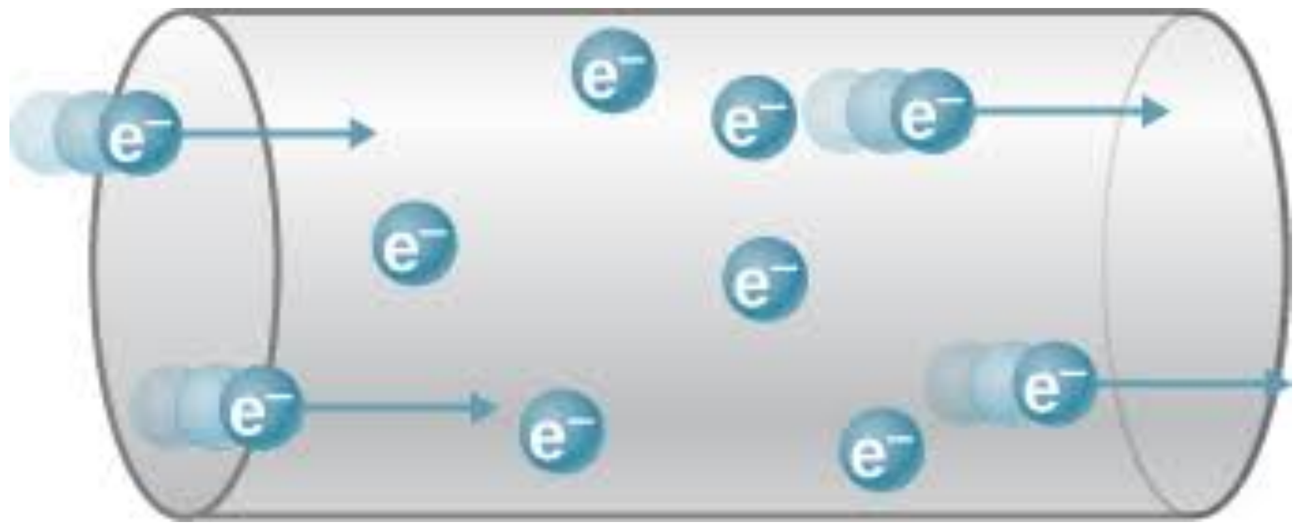
Quantum Boltzmann equation (Landau)
Dense gas of electrons

Collisions are also rare in a dense quantum gas at low temperatures because of the Pauli exclusion principle.

Neglect quantum interference (entanglement) between successive collisions



Current flow with electrons in ordinary metals



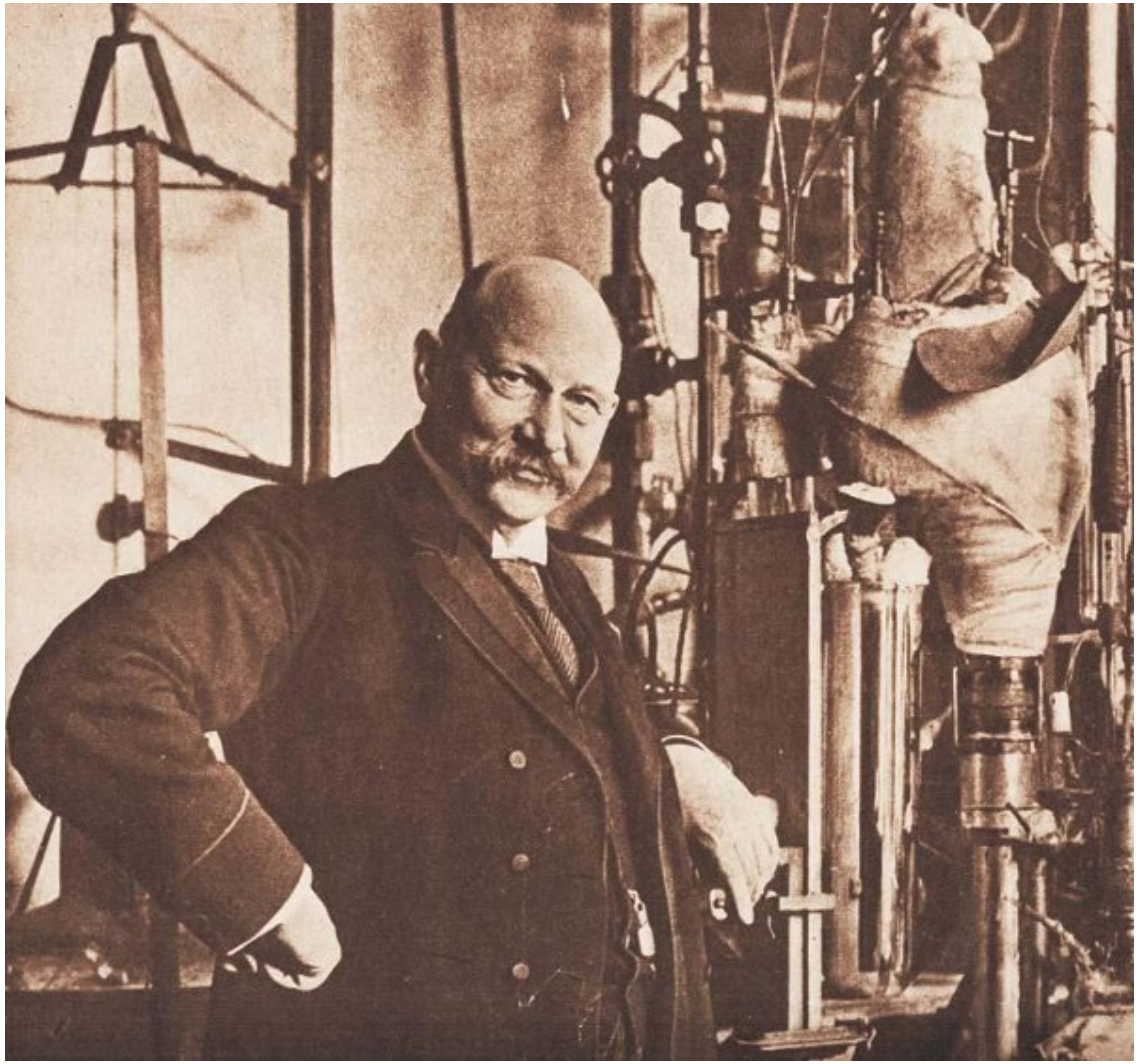
Flow of electrons described by Boltzmann equation $\Rightarrow$
typical scattering time $\tau \sim 1/(UT)^2$ (U is the strength of interactions),
resistivity $\rho(T) = \rho(0) + AT^2$

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

The long scattering time implies that individual electrons are well-defined.

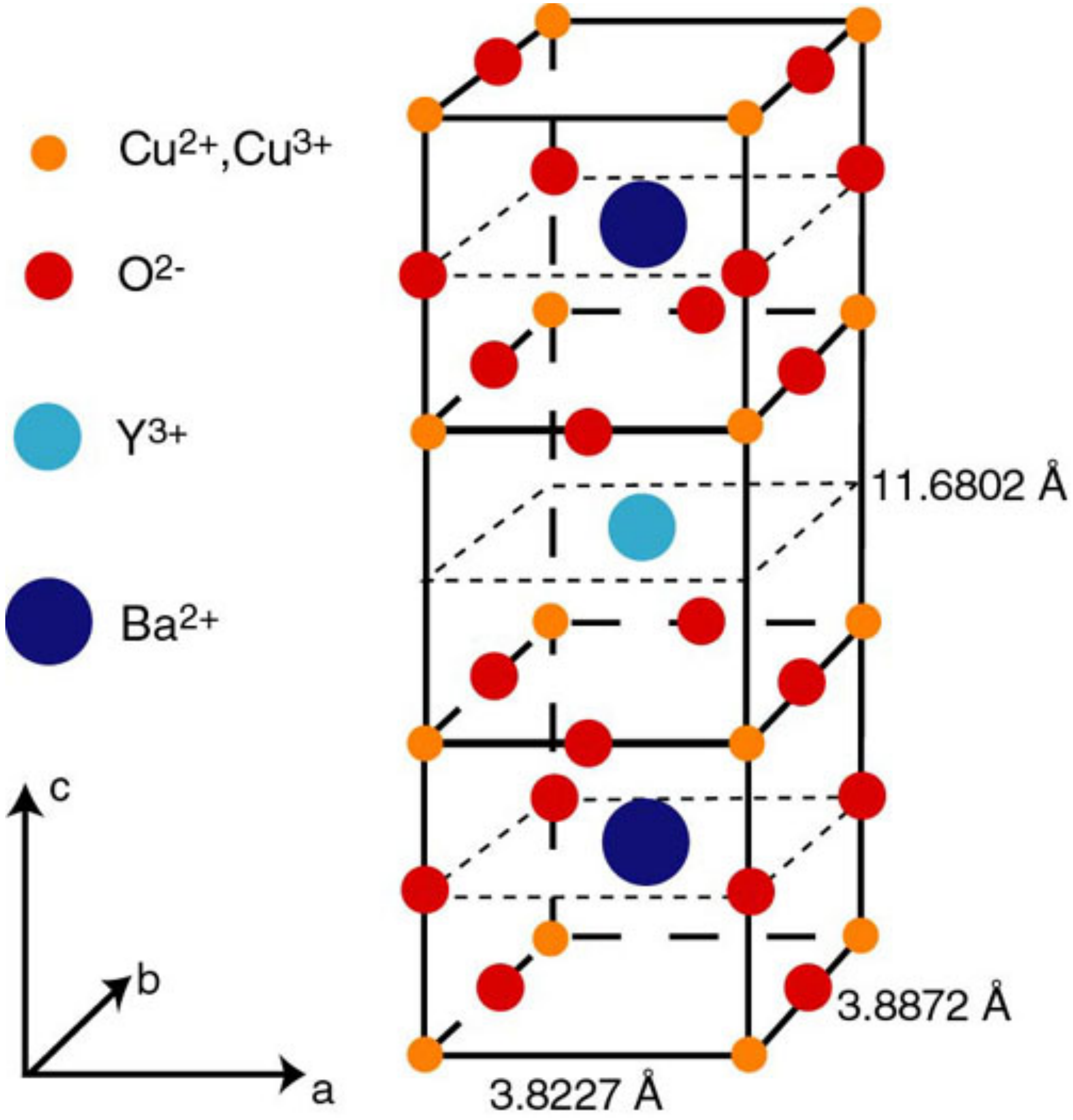
The motion of electrons is 'ballistic' or 'integrable'
up to the long time τ, after which it is chaotic.

High temperature superconductivity

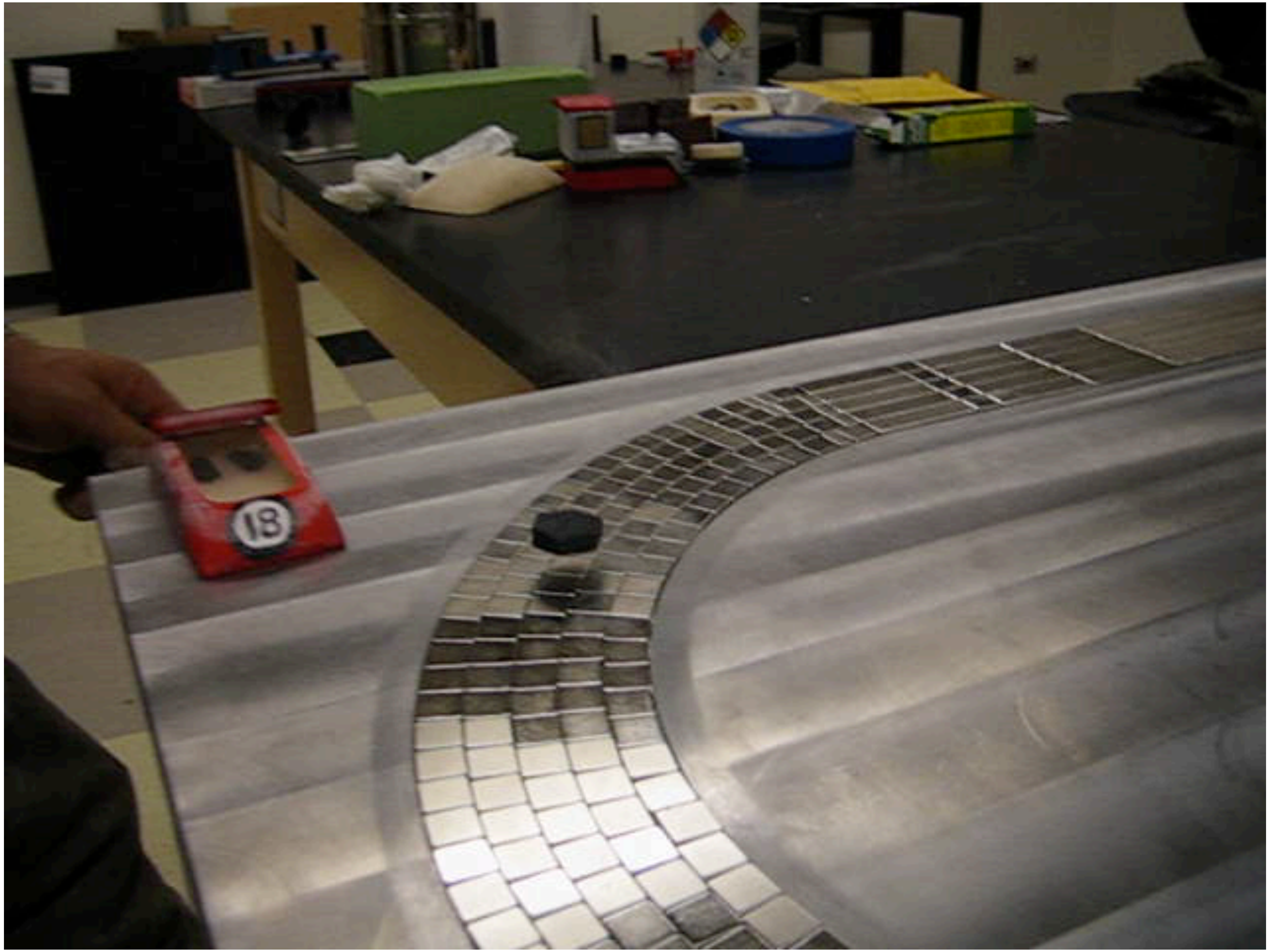


Kamerlingh Onnes 1911:
Mercury is a superconductor below -269 °C

Cuprate high temperature superconductors



$YBa_2Cu_3O_{6+x}$



Nd-Fe-B magnets, YBaCuO superconductor

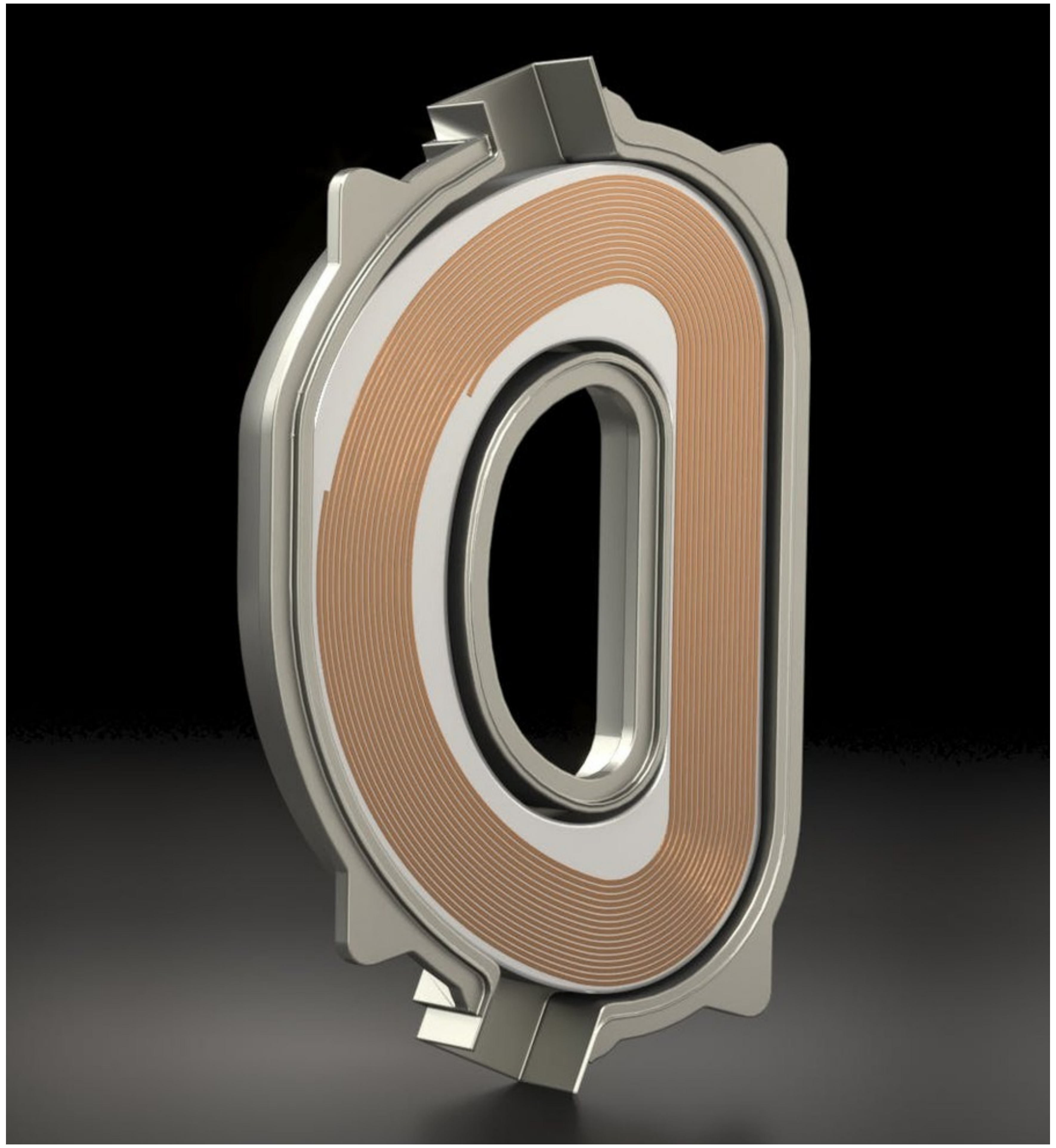
Julian Hetel and Nandini Trivedi, Ohio State University

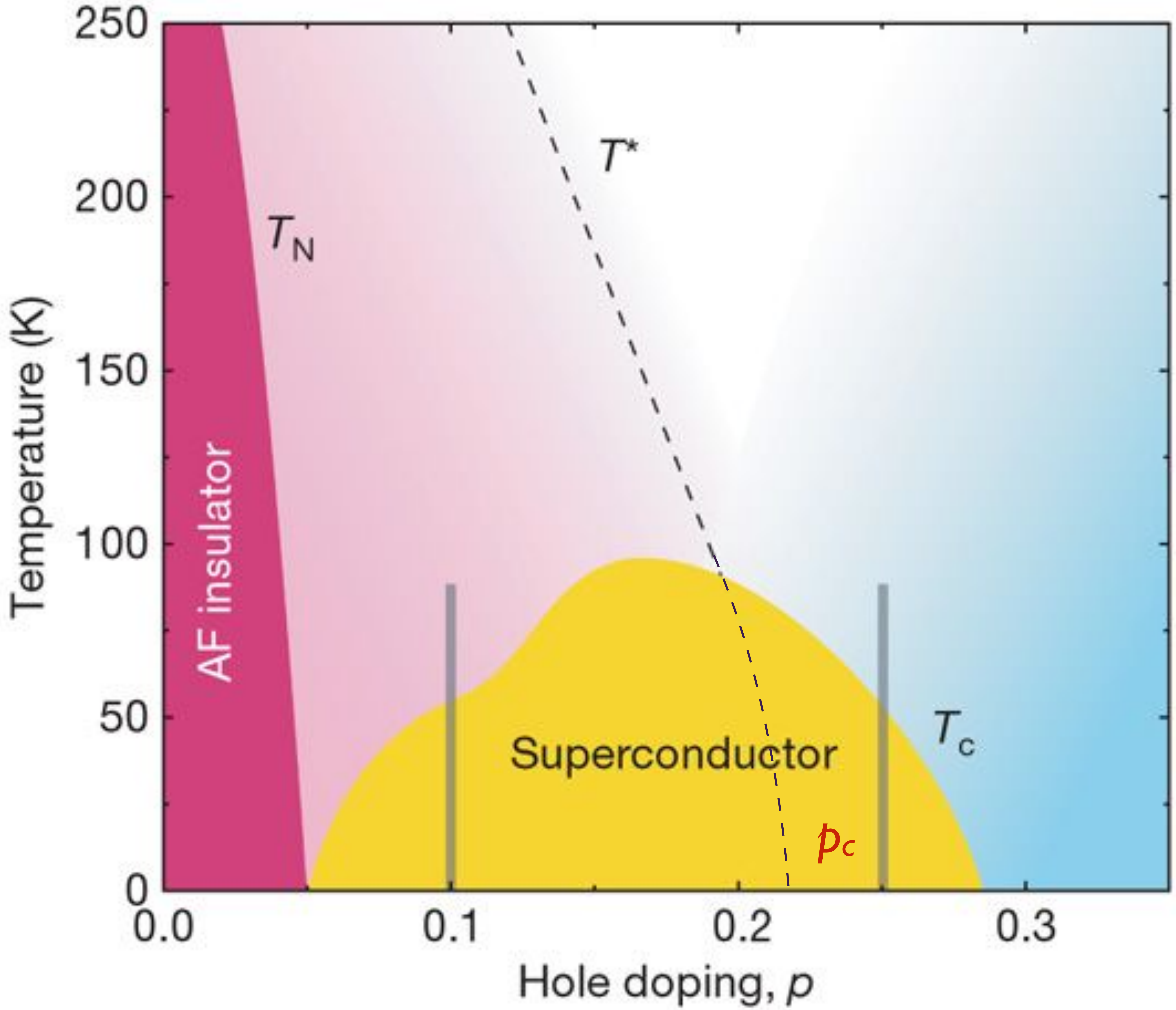
HTS Magnets: Enabling Technology

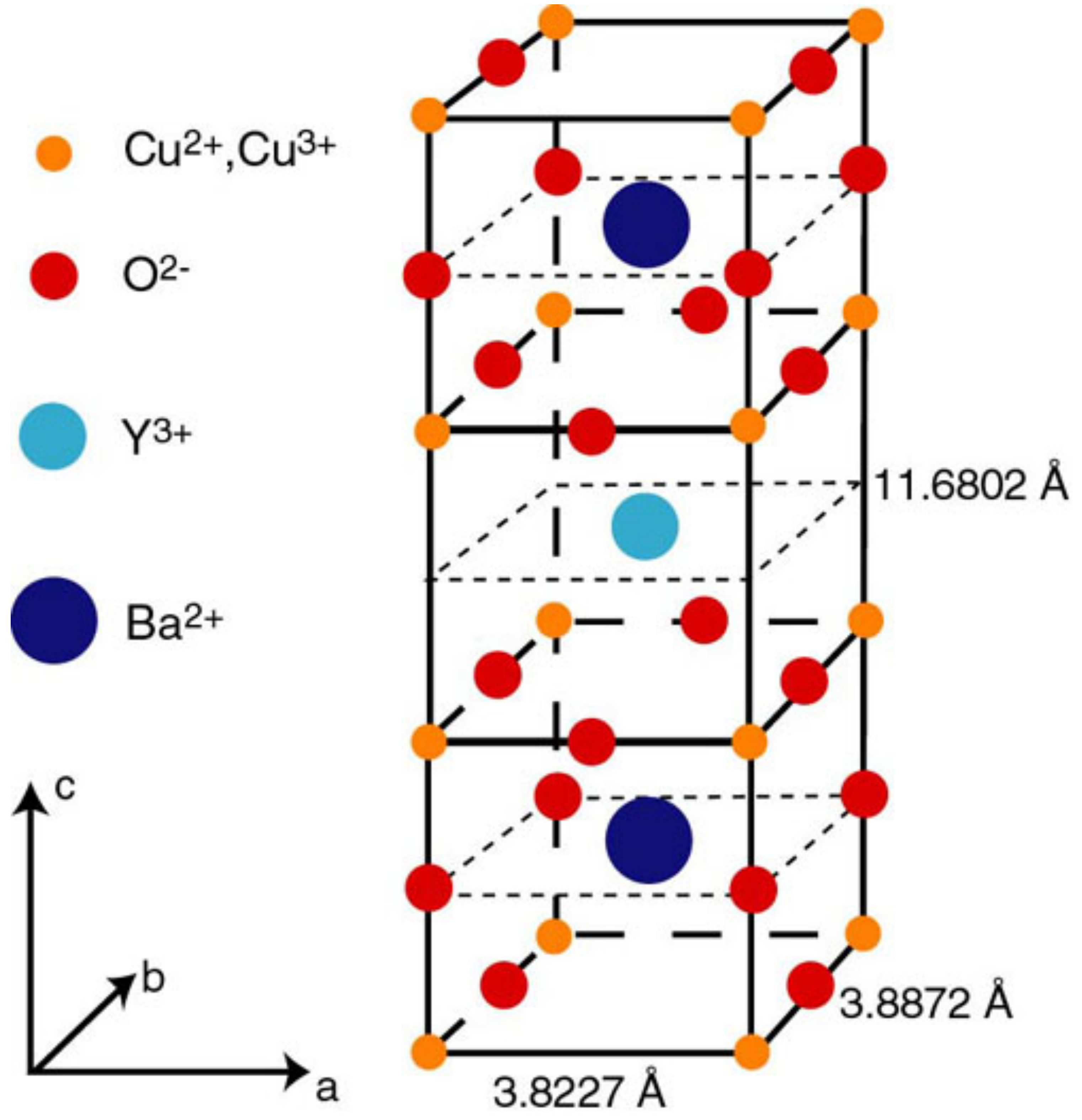
The surest path to limitless, clean, fusion energy

YBCO magnets allow for smaller, faster, and less expensive tokamaks for plasma fusion

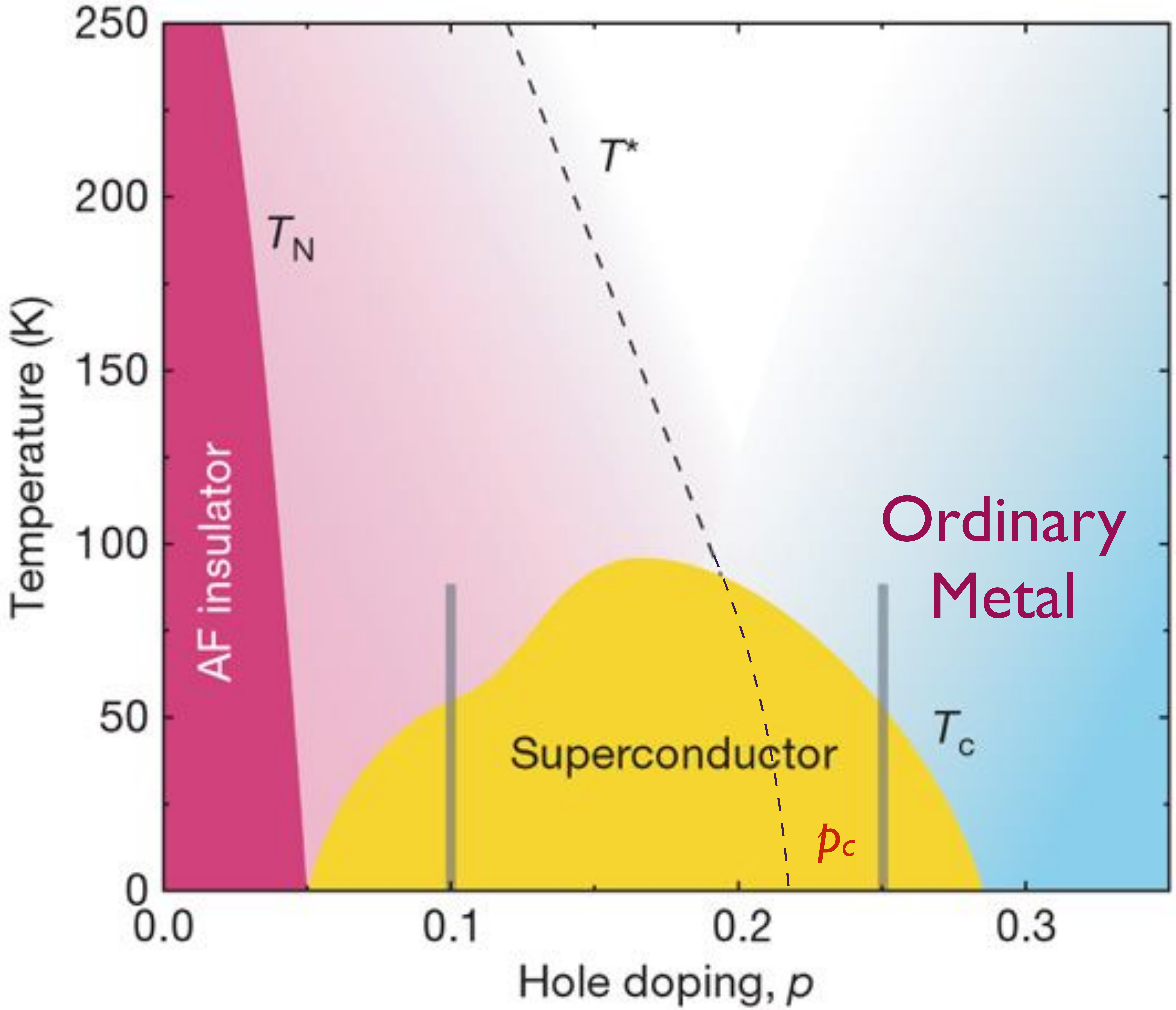
Commonwealth Fusion Systems

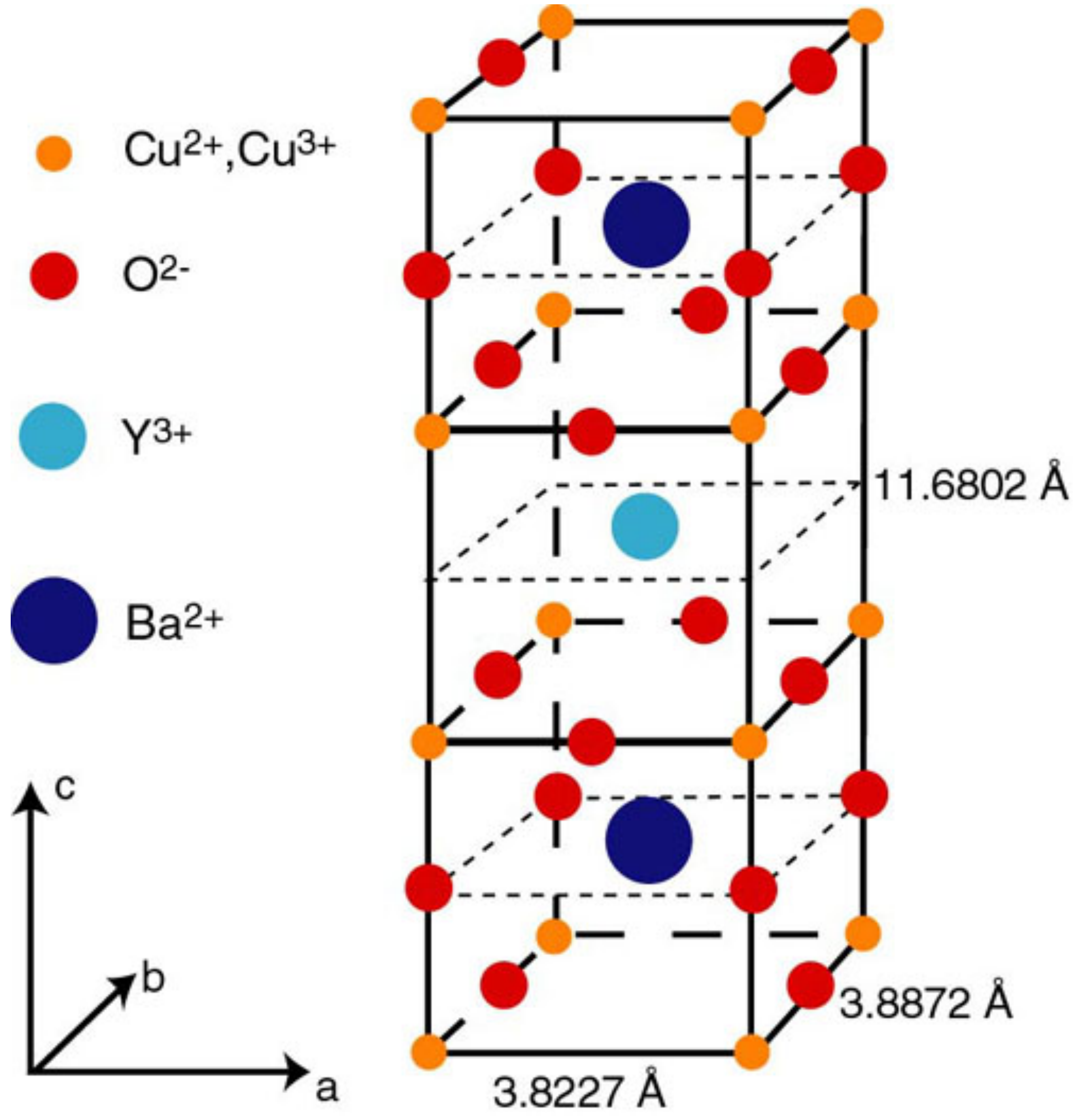



250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Superconductor
T_c
p_c


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

$YBa_2Cu_3O_{6+x}$


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


Cu2+,Cu3+
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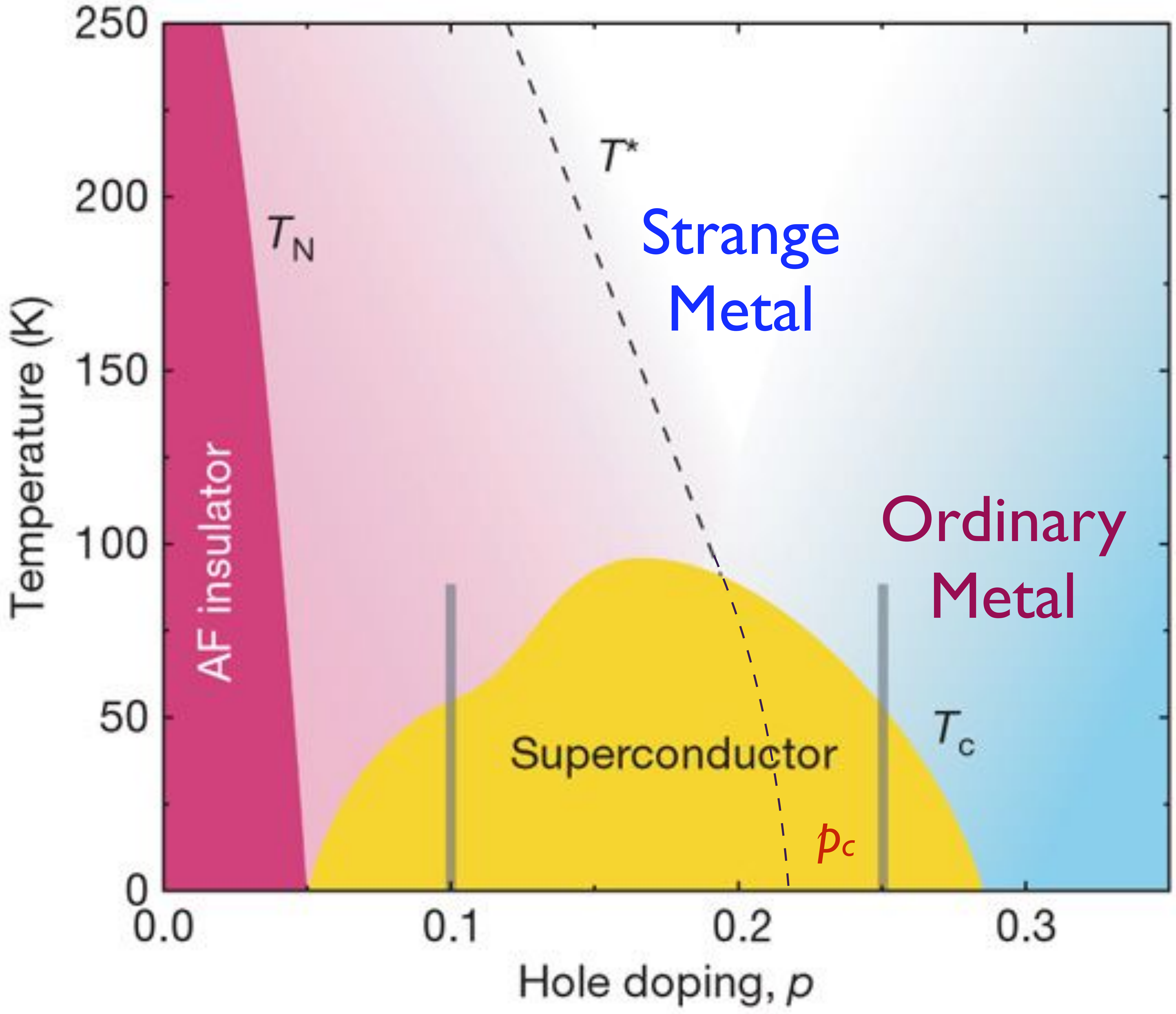
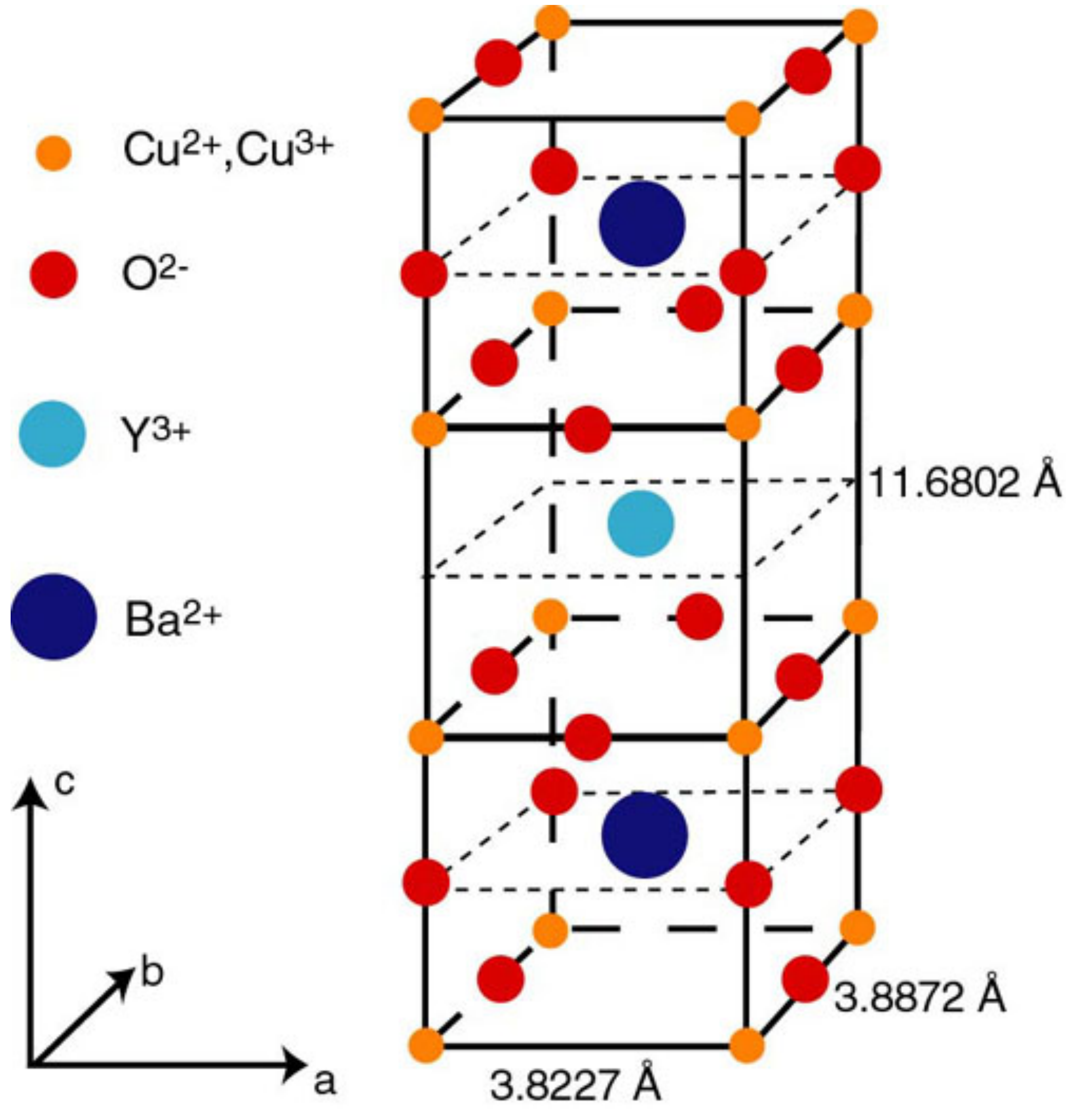

250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T^*
Strange
Metal
Ordinary
Metal
Superconductor
T_c
p_c


Cu^{2+},Cu^{3+}
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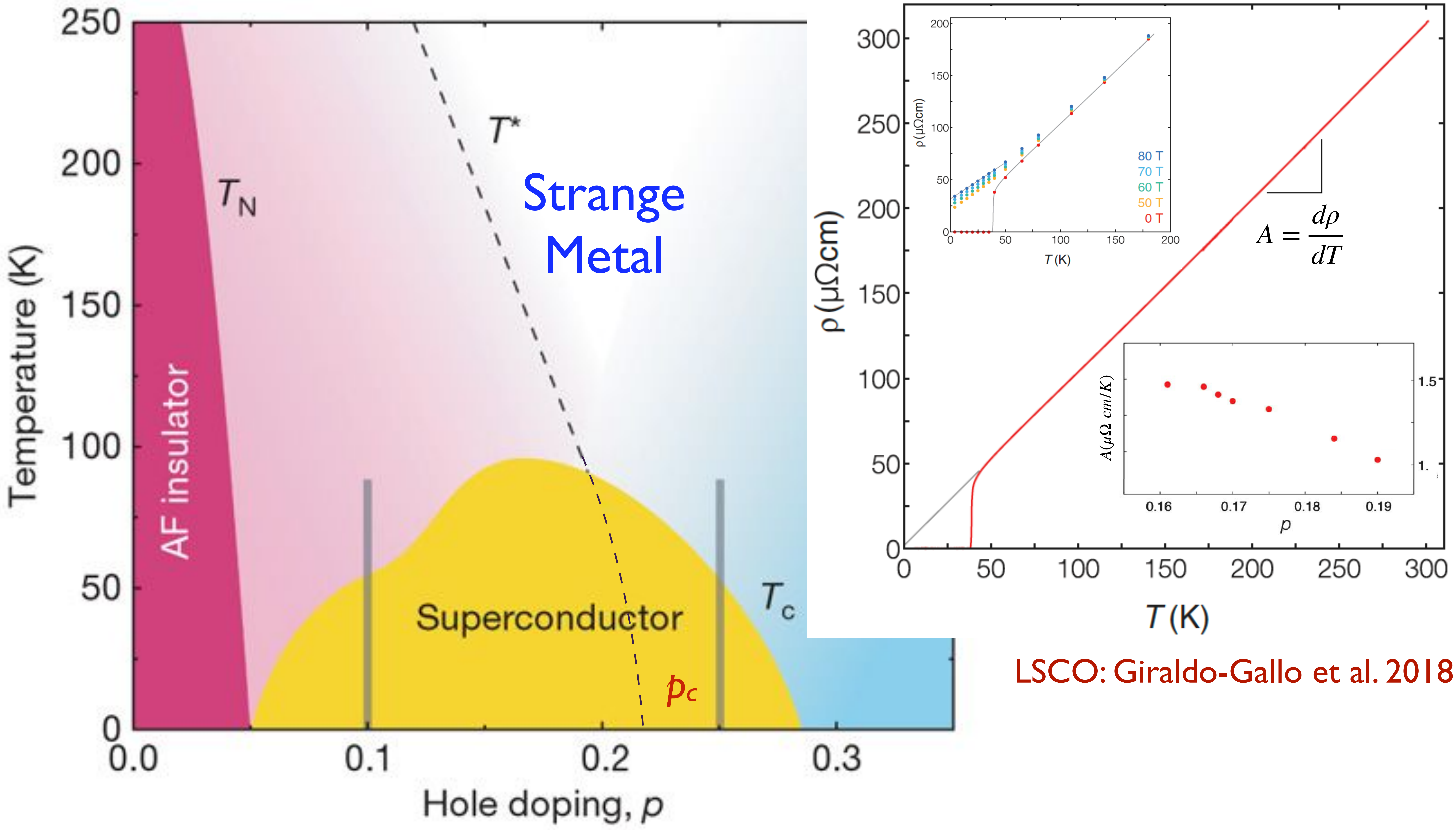


LSCO: Giraldo-Gallo et al. 2018

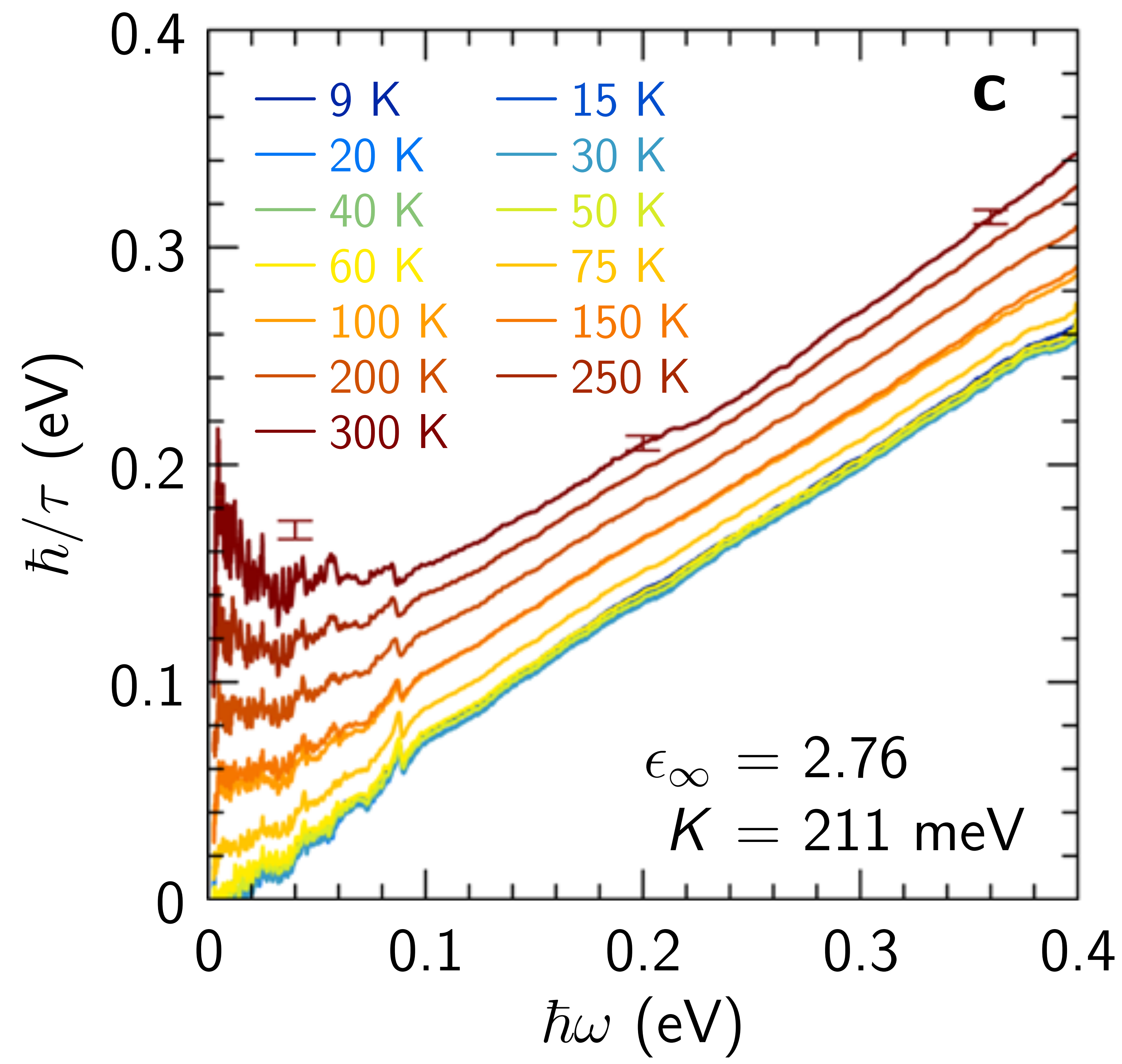
Reconciling scaling of the optical conductivity of cuprate superconductors with Planckian resistivity and specific heat

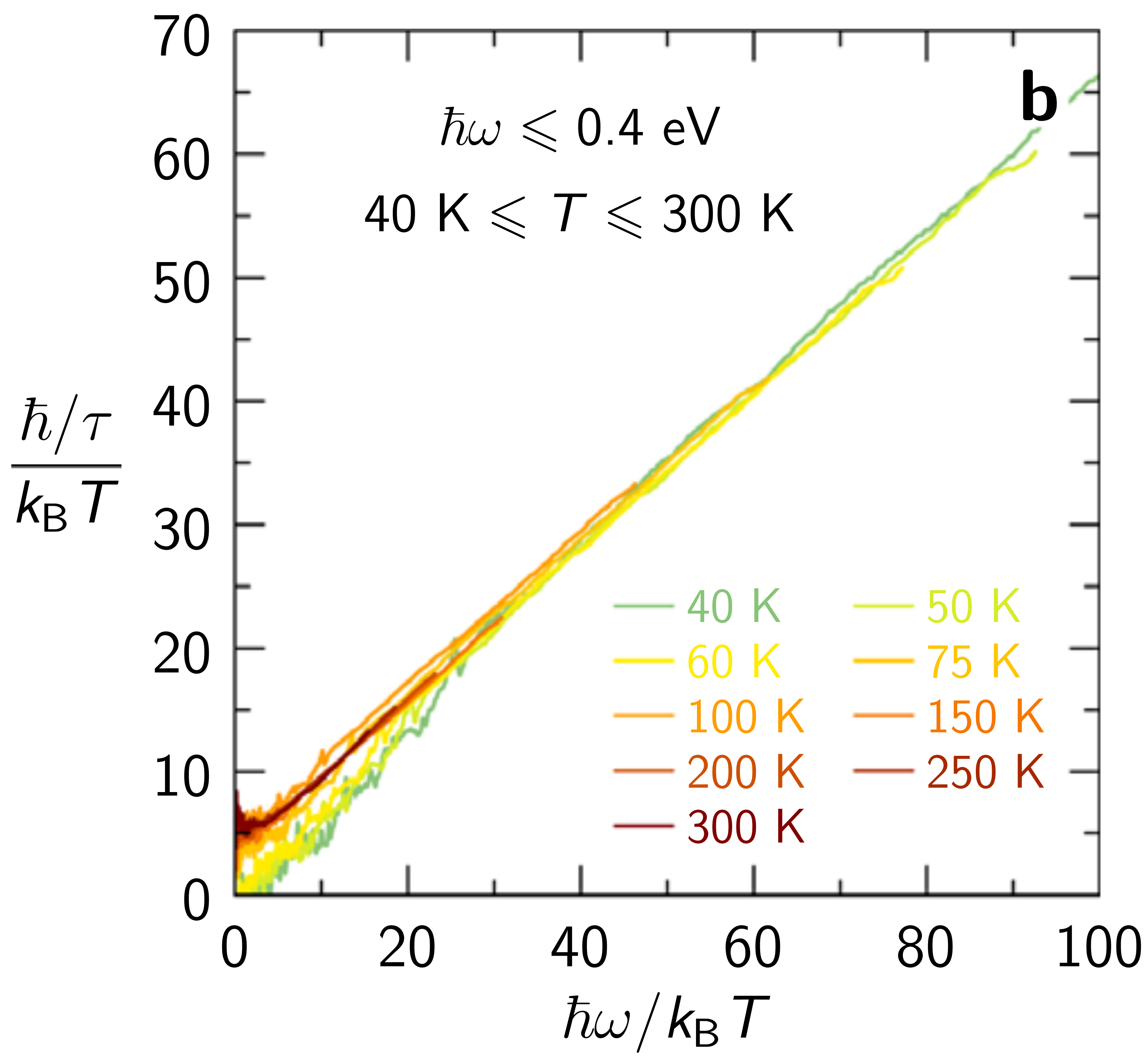
B. Michon, C. Berthod, C. W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges

Nature Communications **14**, Article number: 3033 (2023)

$$\sigma(\omega) = i\frac{e^2K/(\hbar d_c)}{\hbar\omega\frac{m^*(\omega)}{m} + i\frac{\hbar}{\tau(\omega)}}$$

Planckian dynamics!



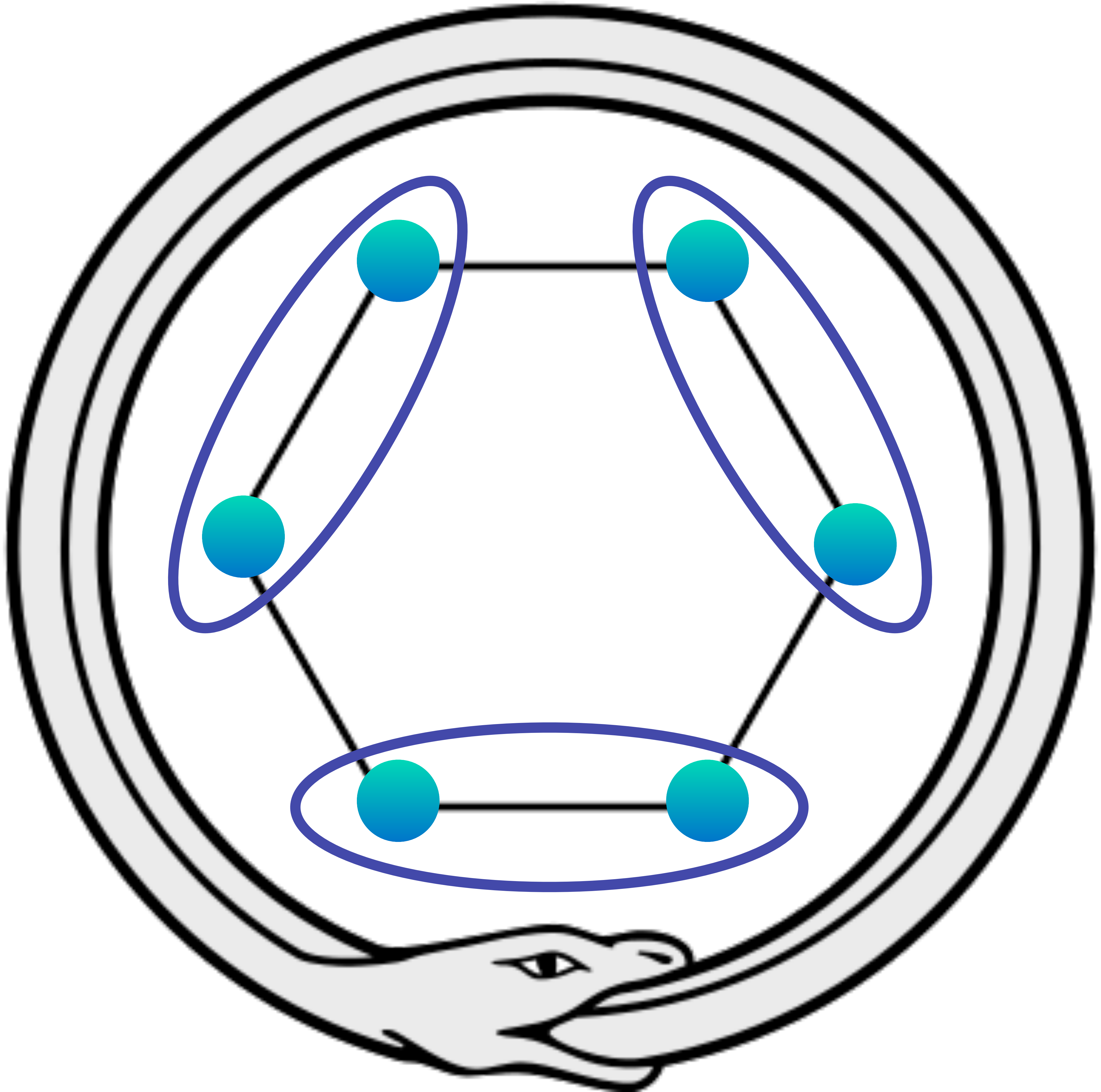


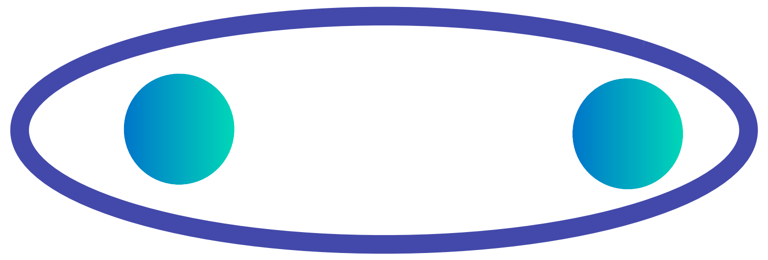
$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$

Quantum entanglement (1865)

Kekule’s spooky dream (1865)

Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail*



 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Benzene

*Wikipedia

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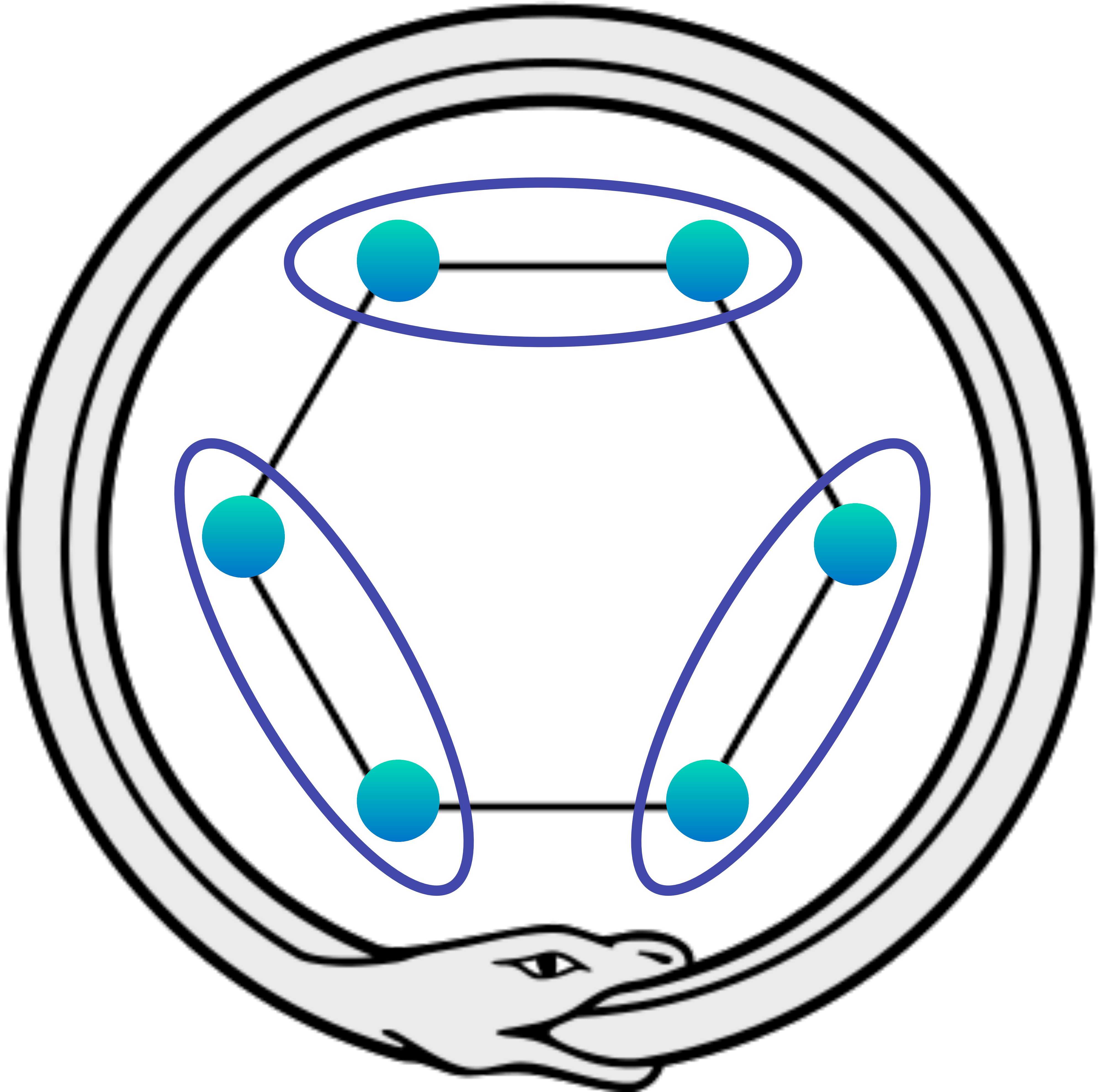
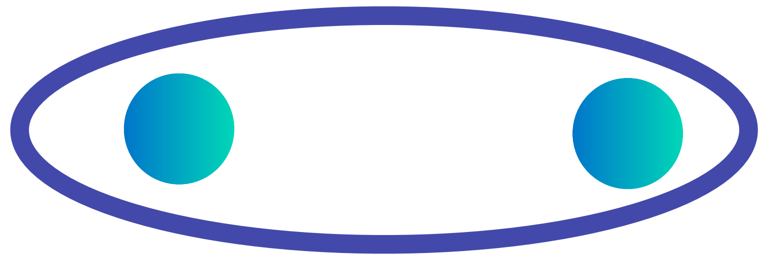


 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Benzene

*Wikipedia

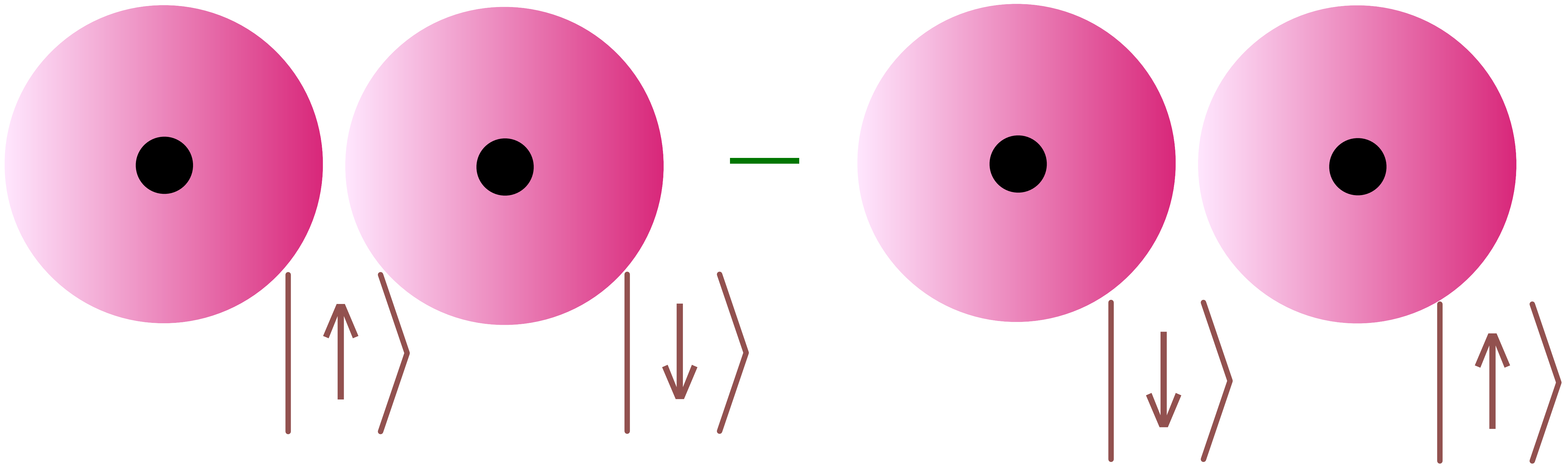
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



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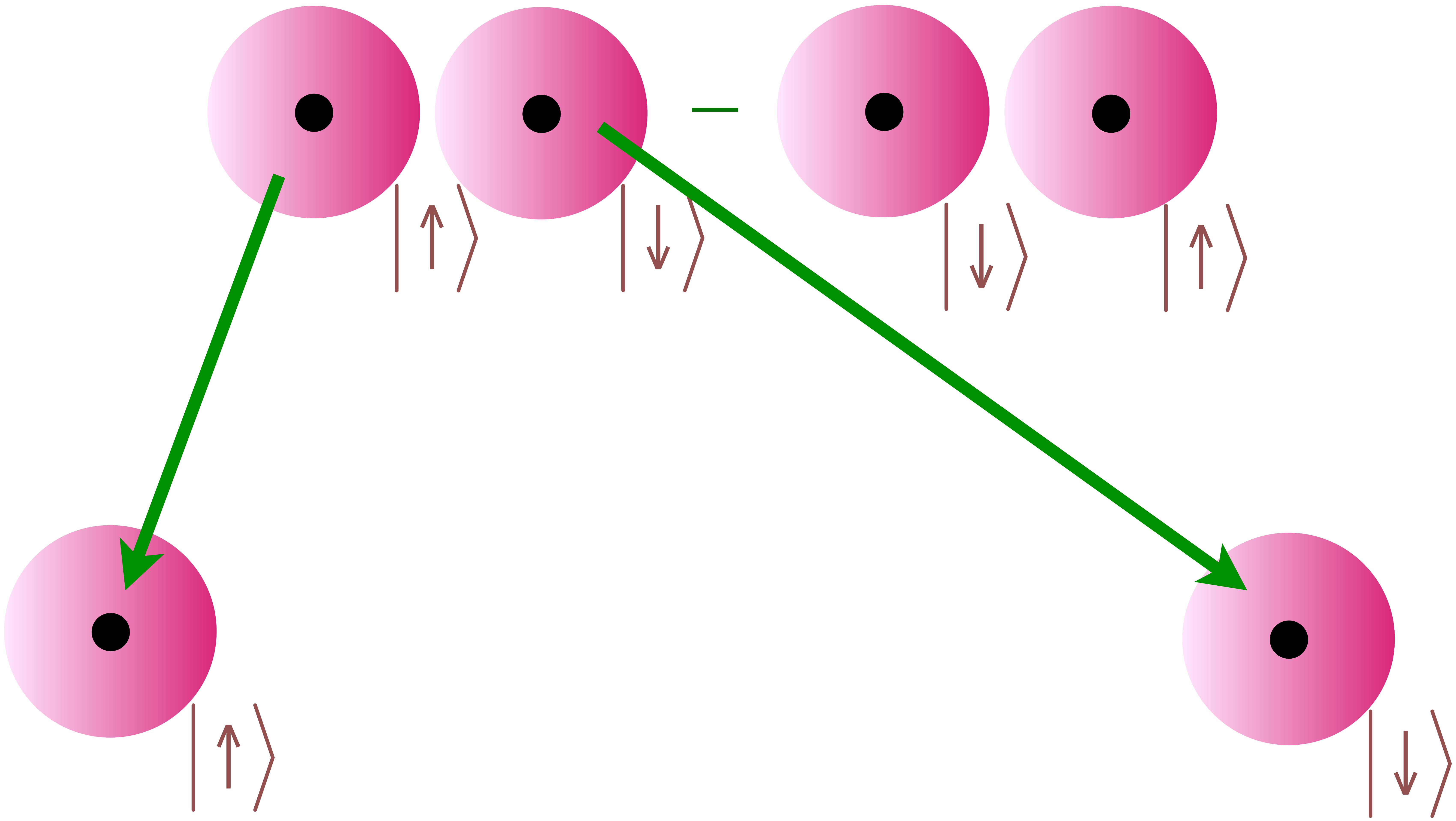
Einstein, Podolsky, Rosen (1935)



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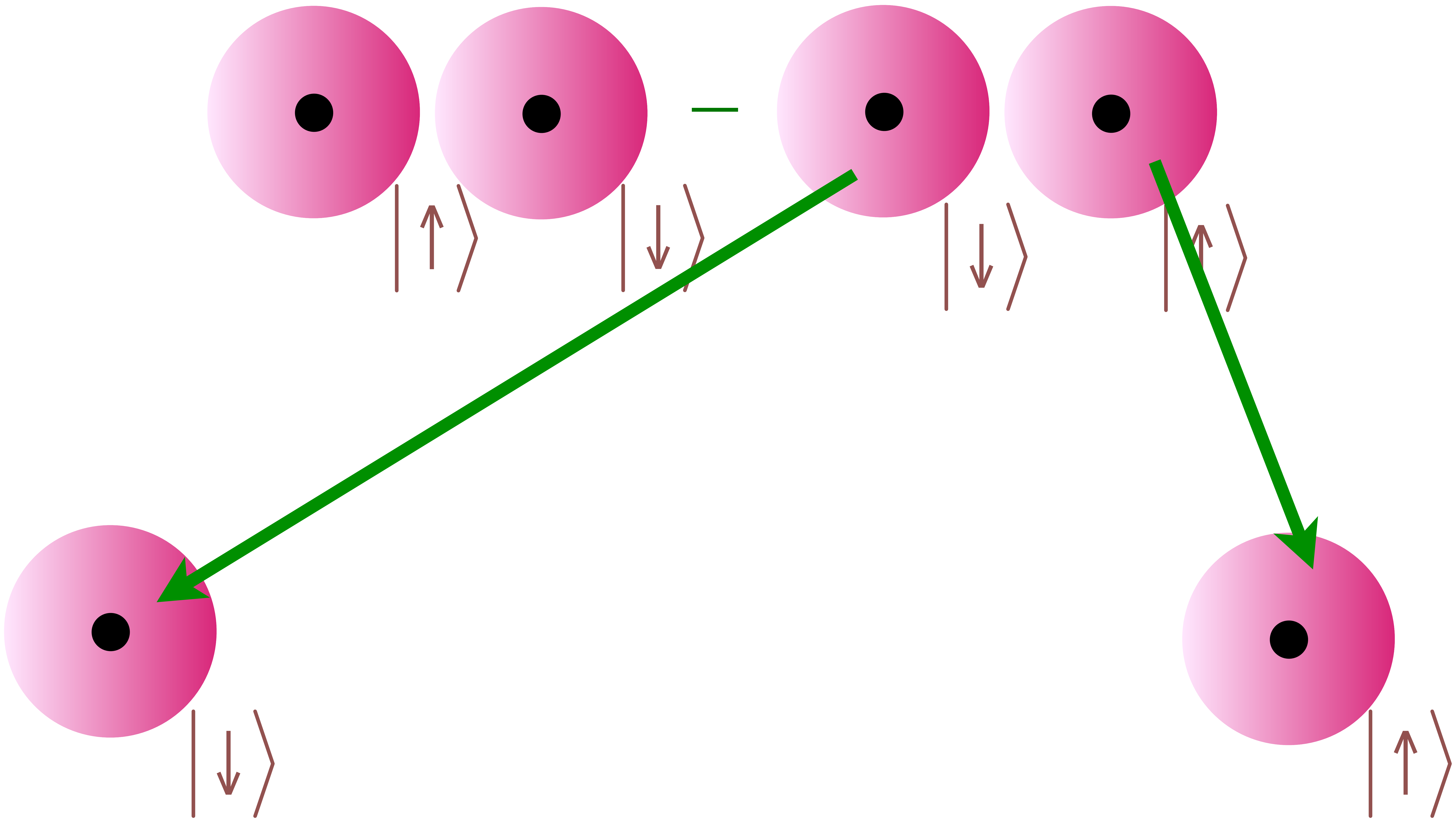

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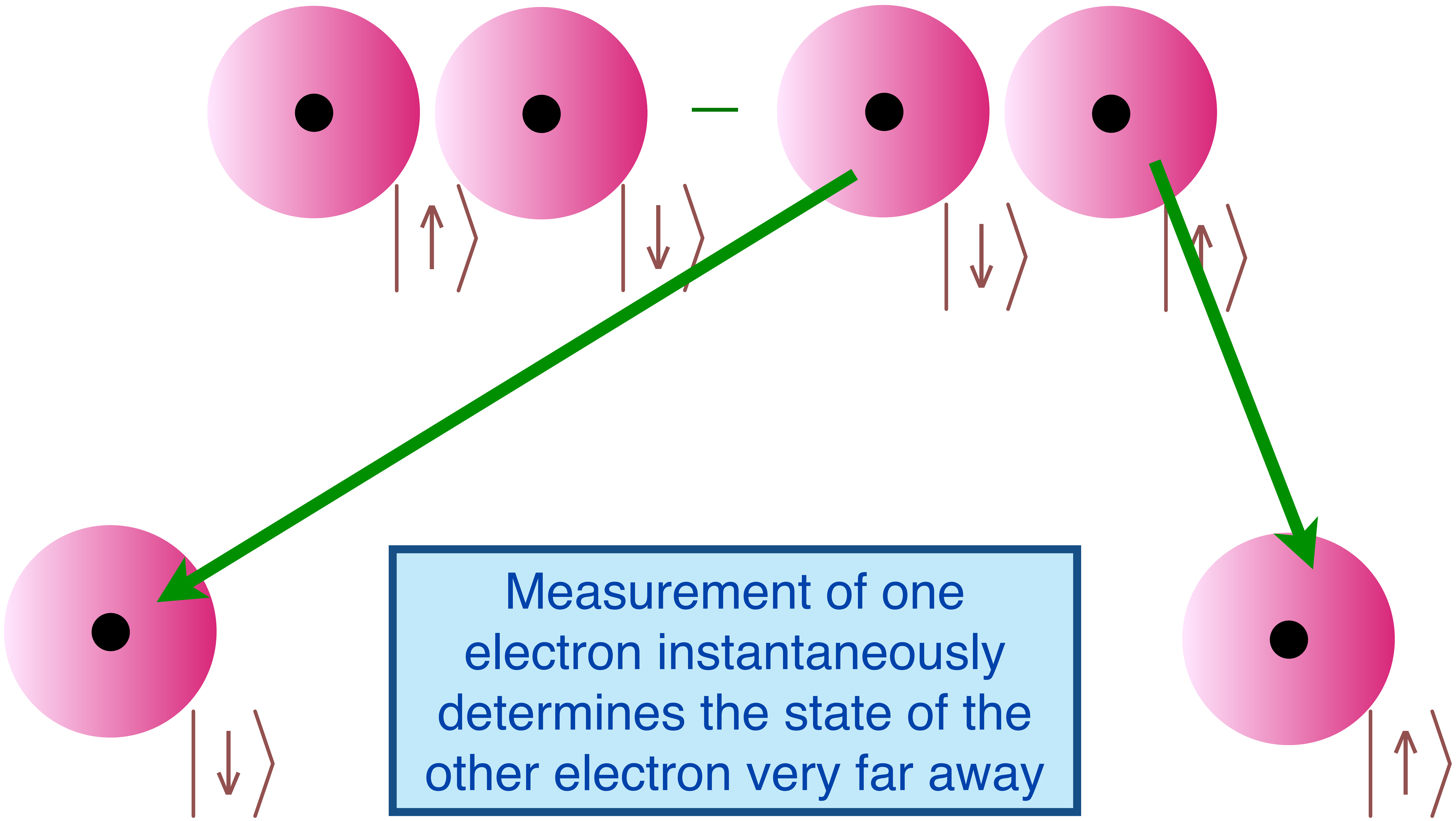
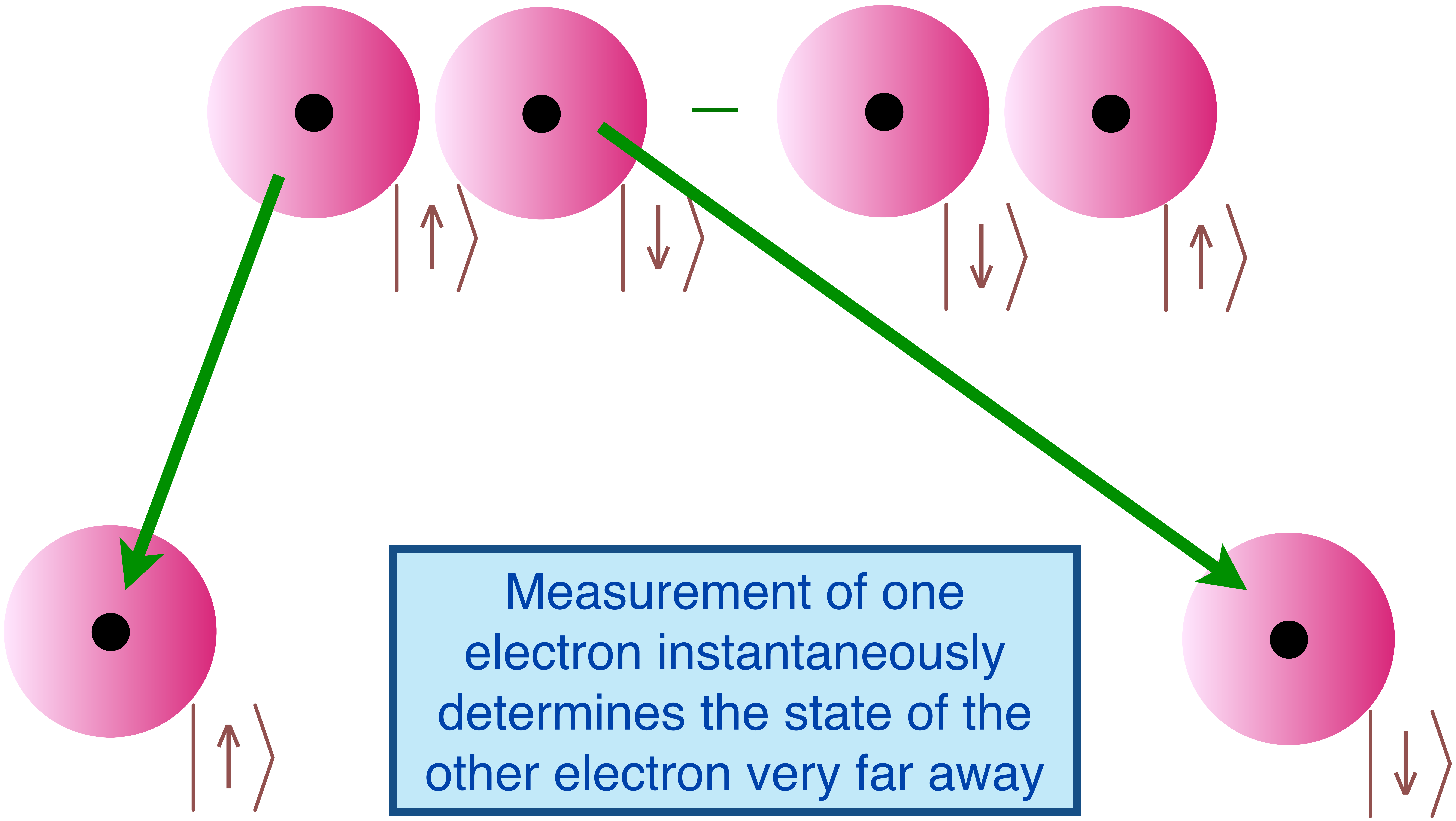
Einstein, Podolsky, Rosen (1935)



Measurement of one electron instantaneously determines the state of the other electron very far away

Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



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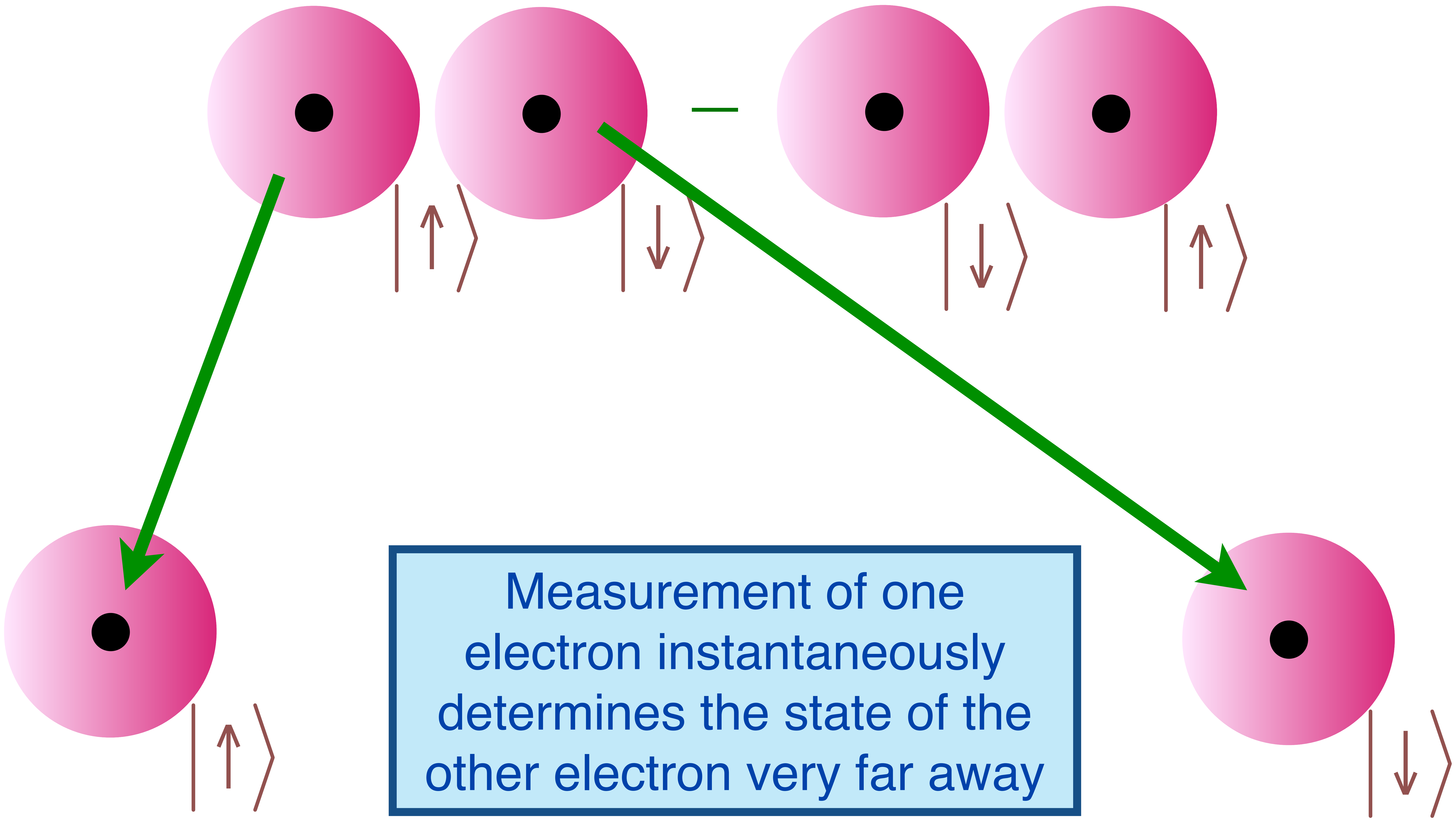

Spooky action at a distance !

deren Notwendigkeit im
mus ja zuerst von Dir klar erkannt wurde, einen
Wahrheitsgehalt hat. Ich kann aber deshalb nicht ernsthaft dar-
an glauben, weil die Theorie mit dem Grundsatz unvereinbar
ist, daß die Physik eine Wirklichkeit in Zeit und Raum darstel-
len soll, ohne spukhafte Fernwirkungen. Allerdings bin ich
überzeugt, daß es wirklich mit der Theorie

I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at distance

Albert Einstein to Max Born, 3 March 1947

Needed,
to solve open problems in the theory of superconductivity and black holes:

A solvable model of quantum entanglement of $3, 4, 5, \ldots \infty$ particles

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to solve open problems in the theory of superconductivity and black holes:

A solvable model of quantum entanglement of $3, 4, 5, \ldots \infty$ particles

The Sachdev-Ye-Kitaev model of many-particle entanglement

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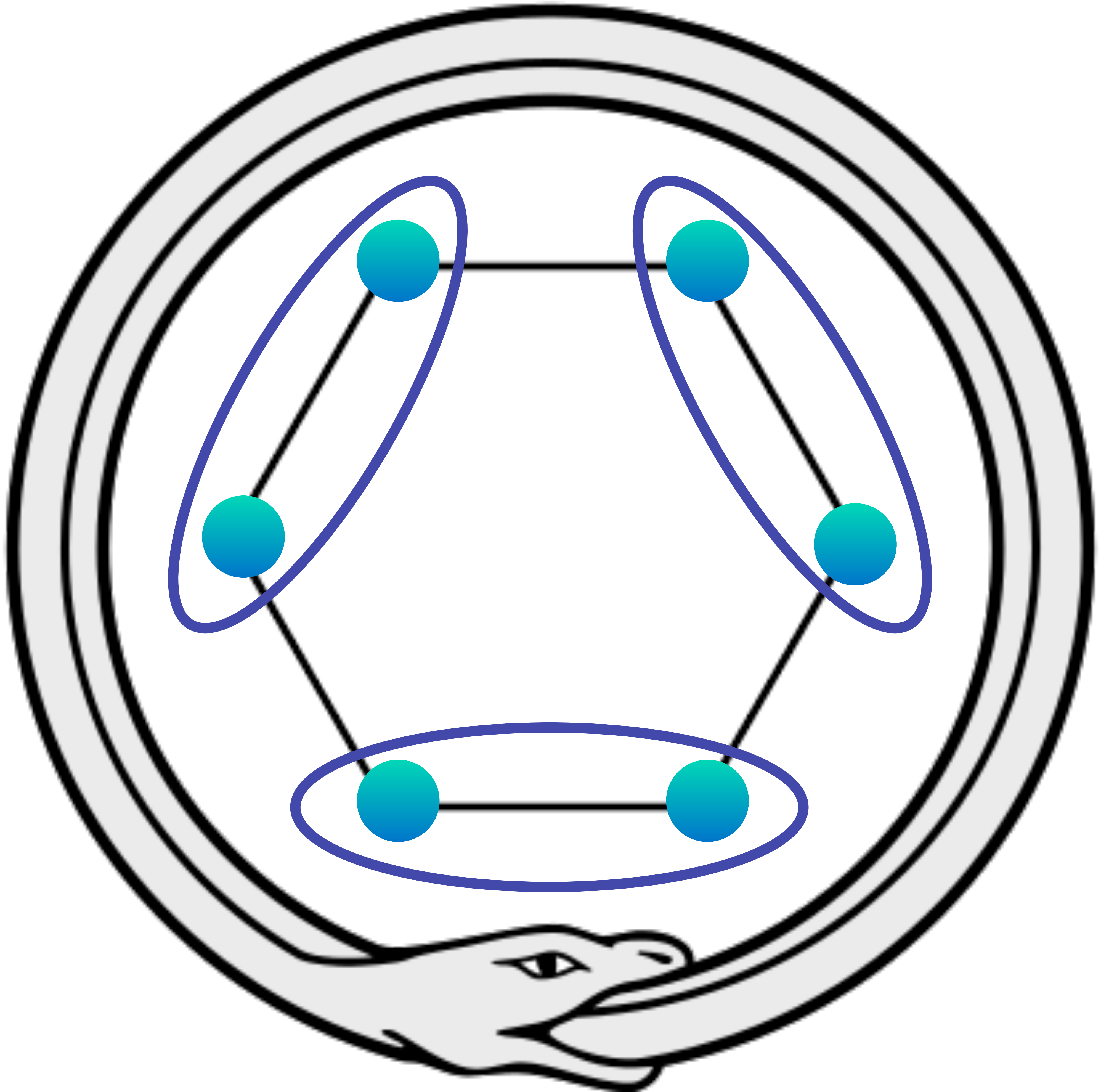
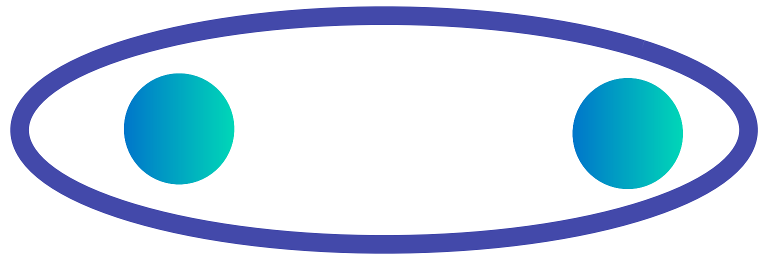
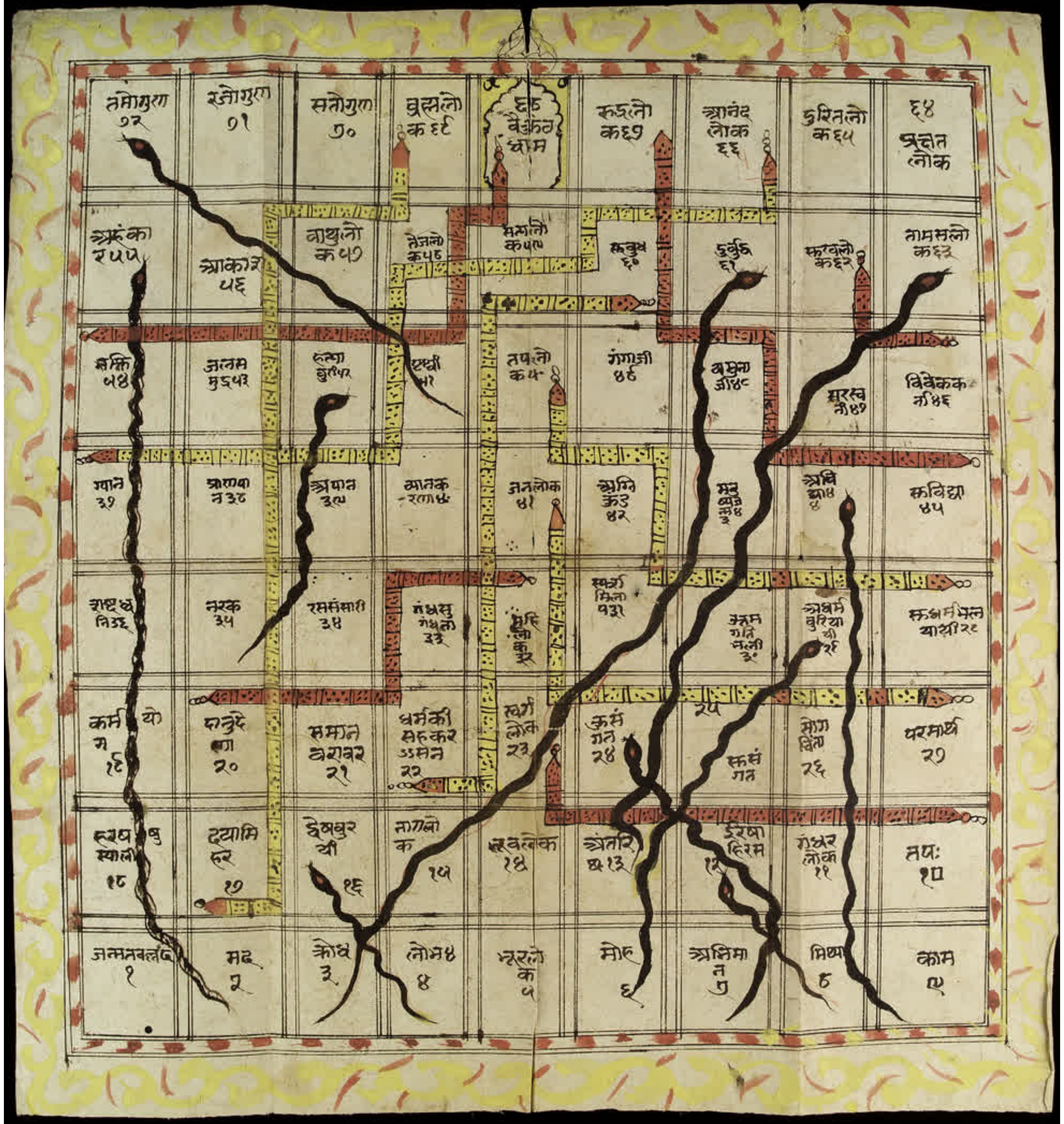



$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Benzene

*Wikipedia



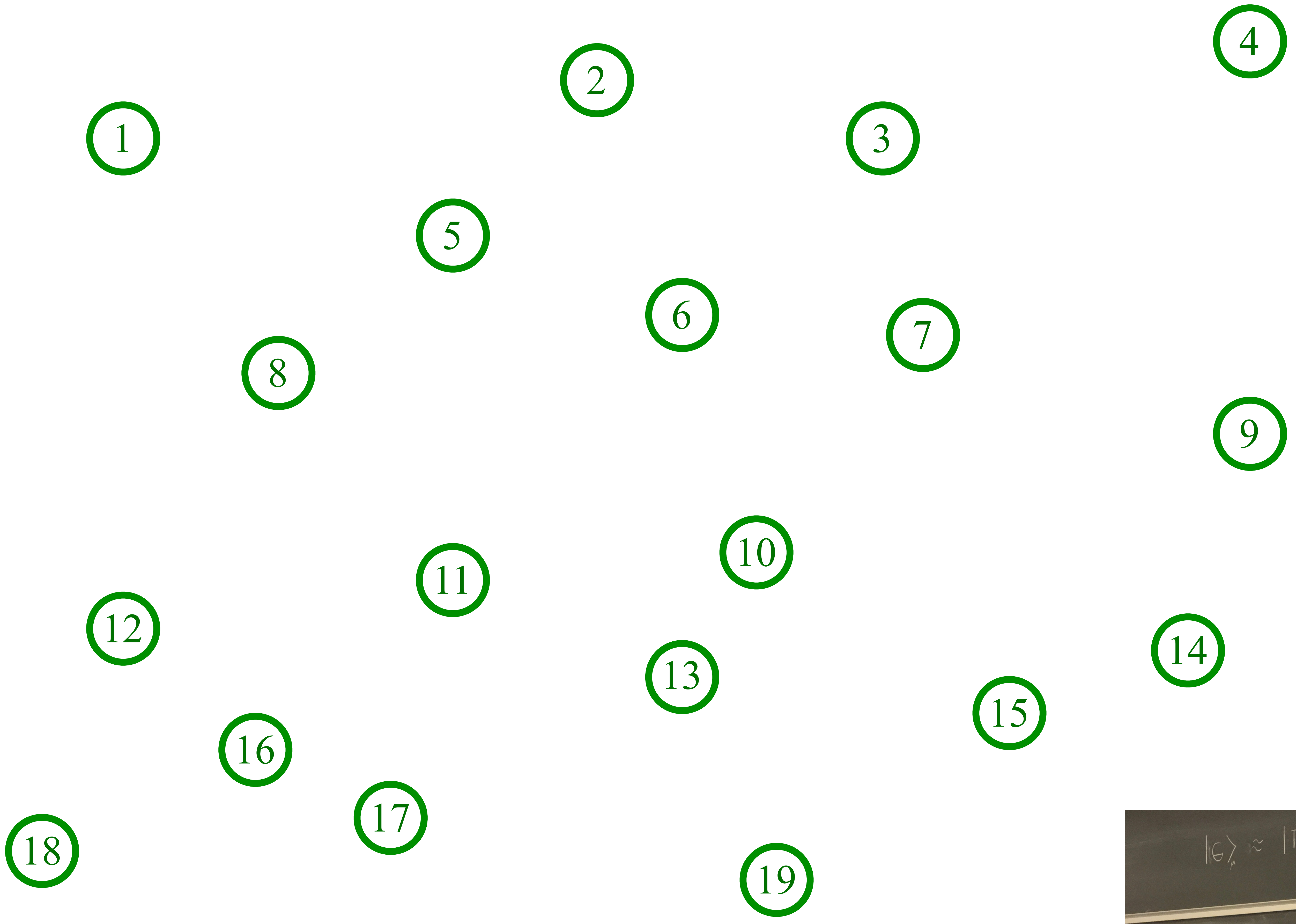
My spooky dream (1992)*

Ancient Indian game of Snakes and Ladders

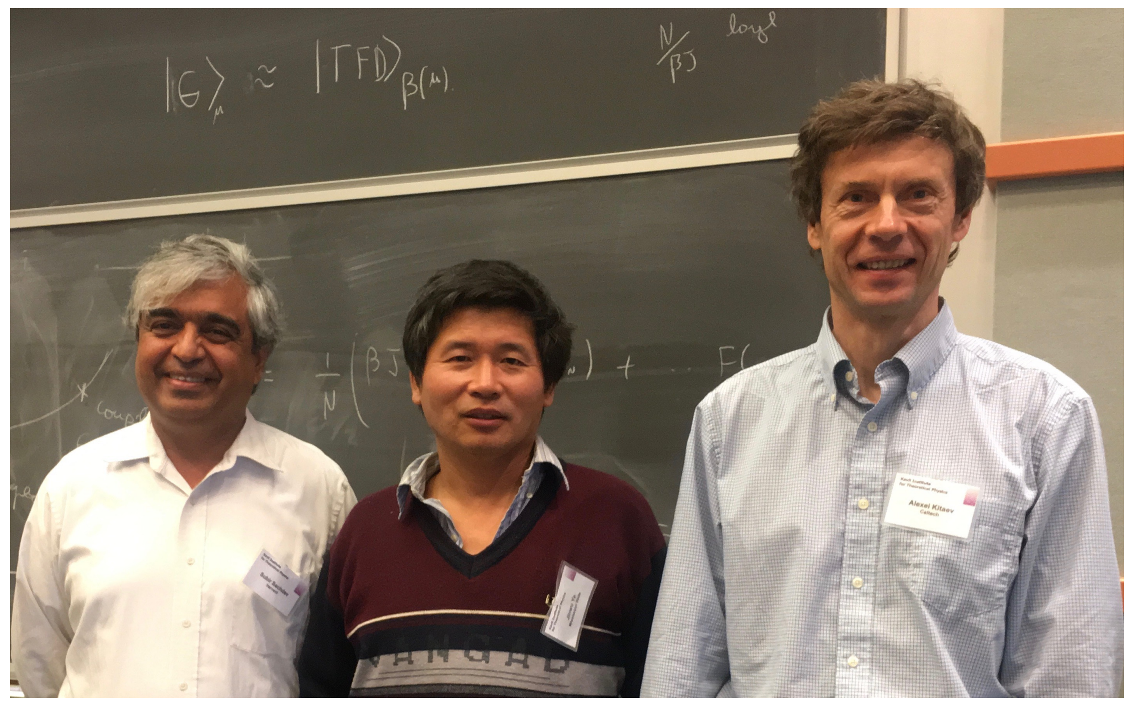
*Not true

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



Pick a set of random positions



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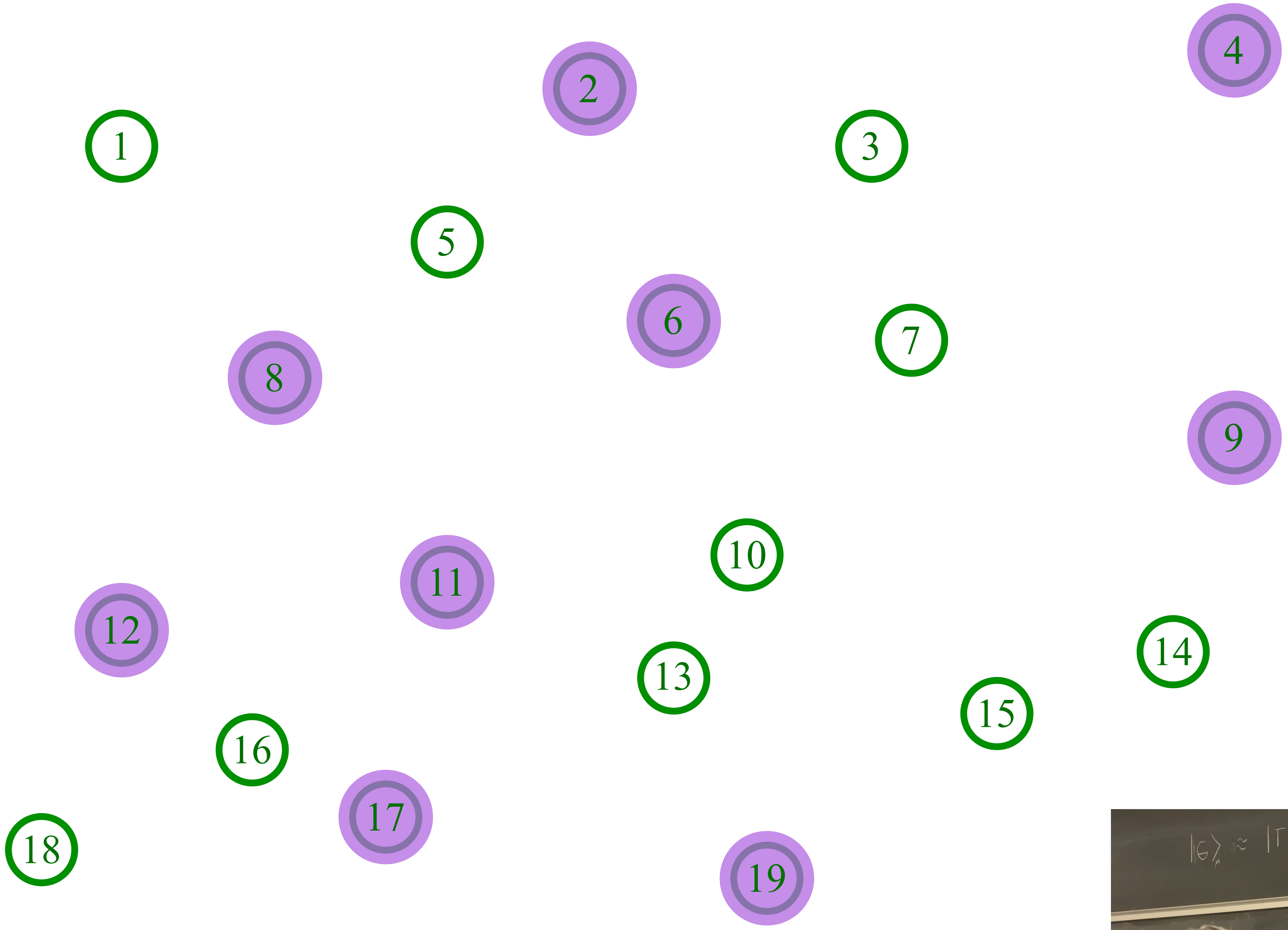
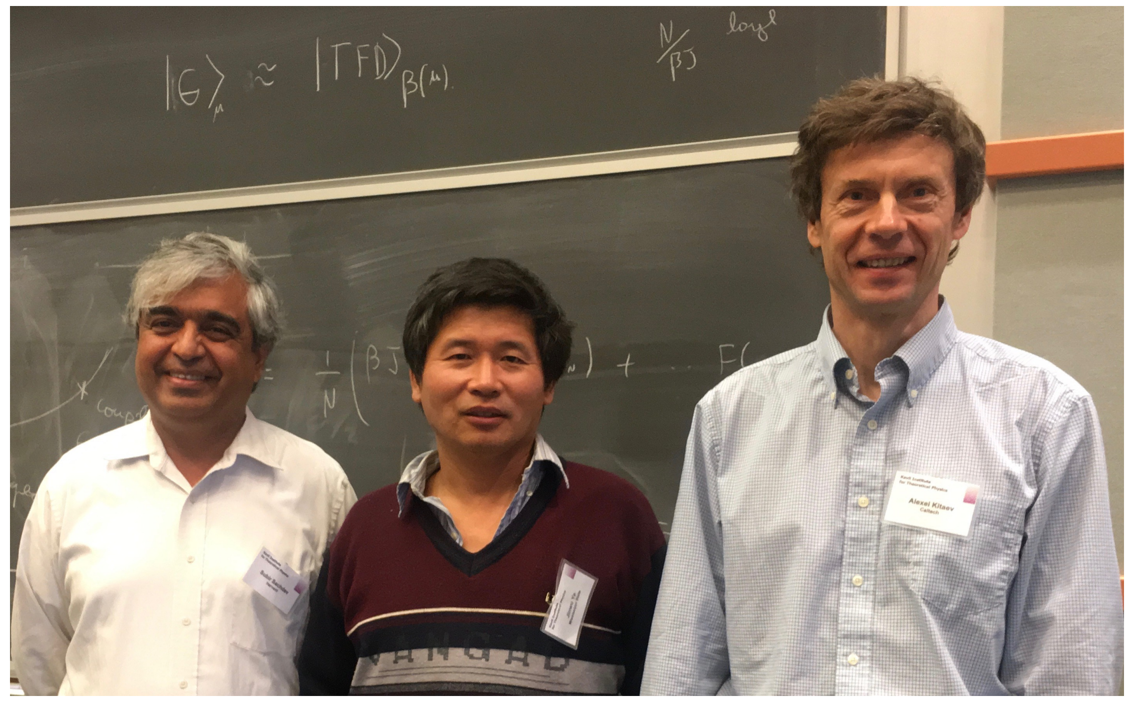
Sachdev, Ye (1993); Kitaev (2015)



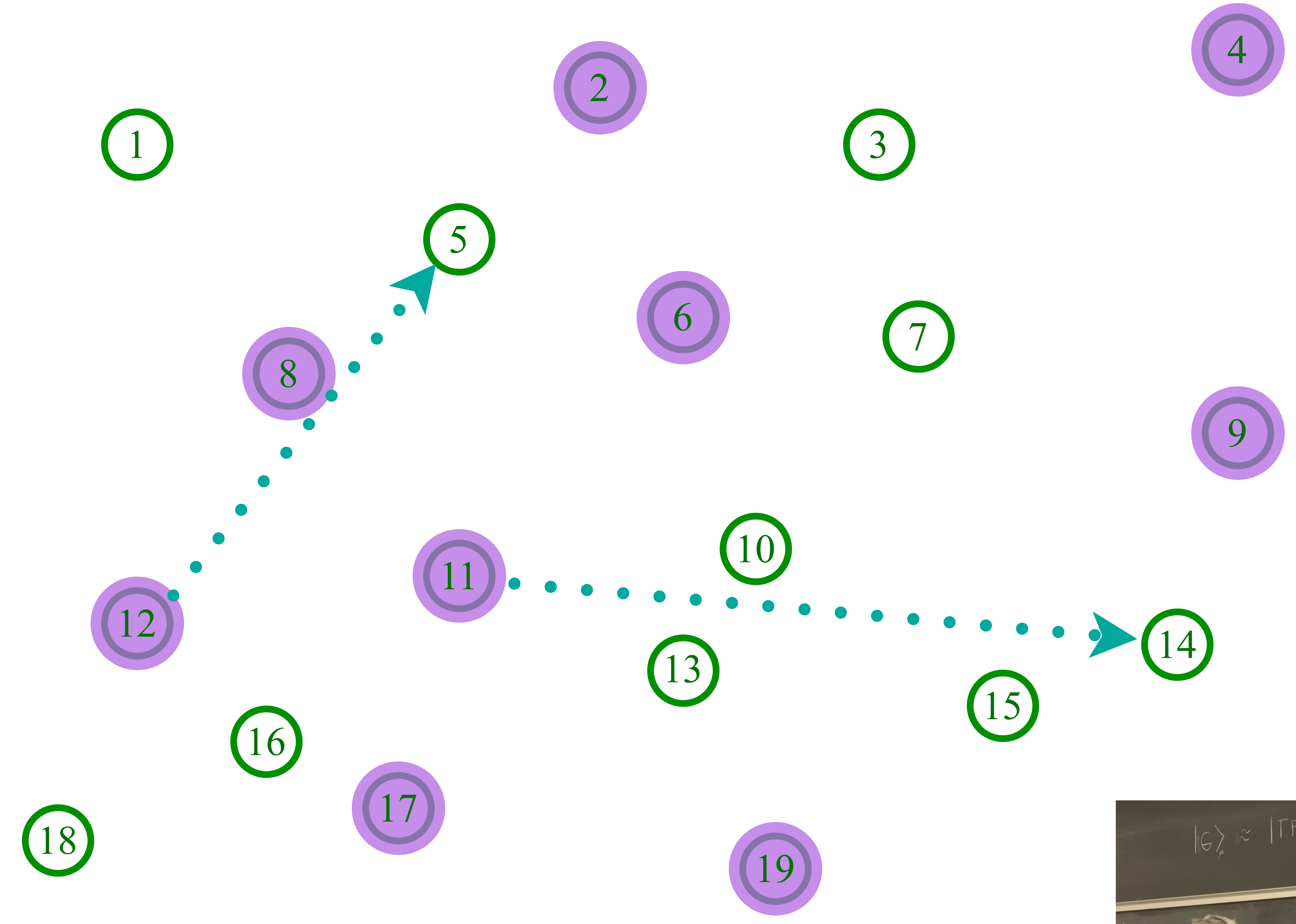
Place electrons randomly on some sites



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{11,12;5,14}$$



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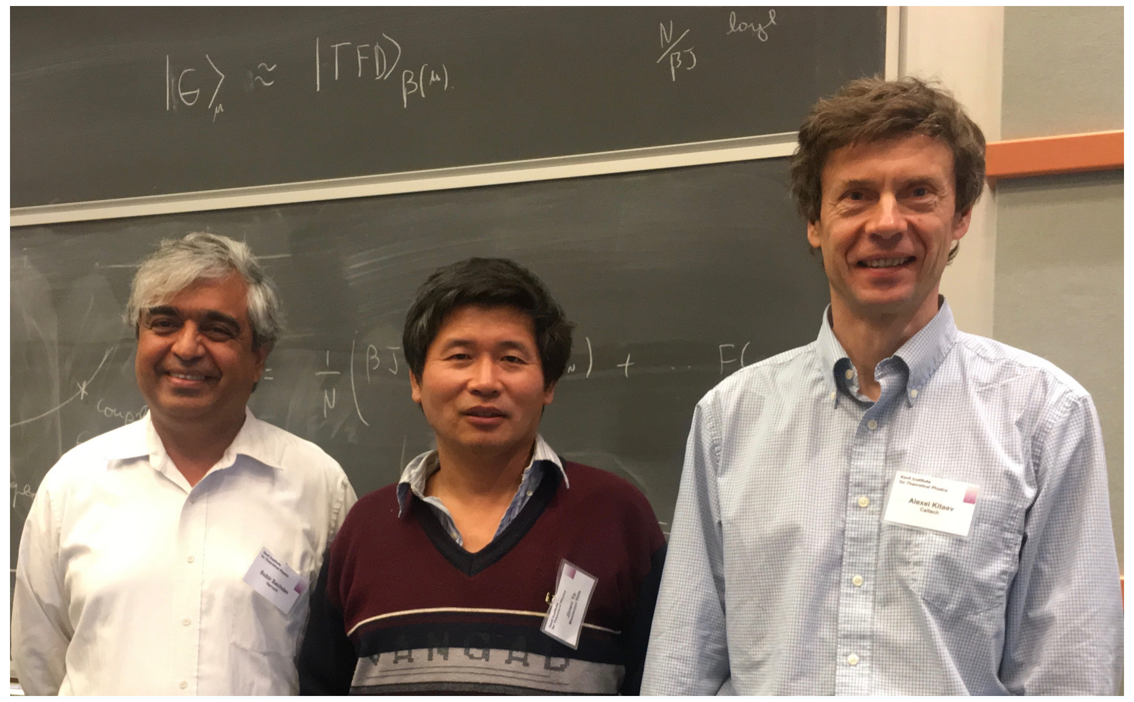

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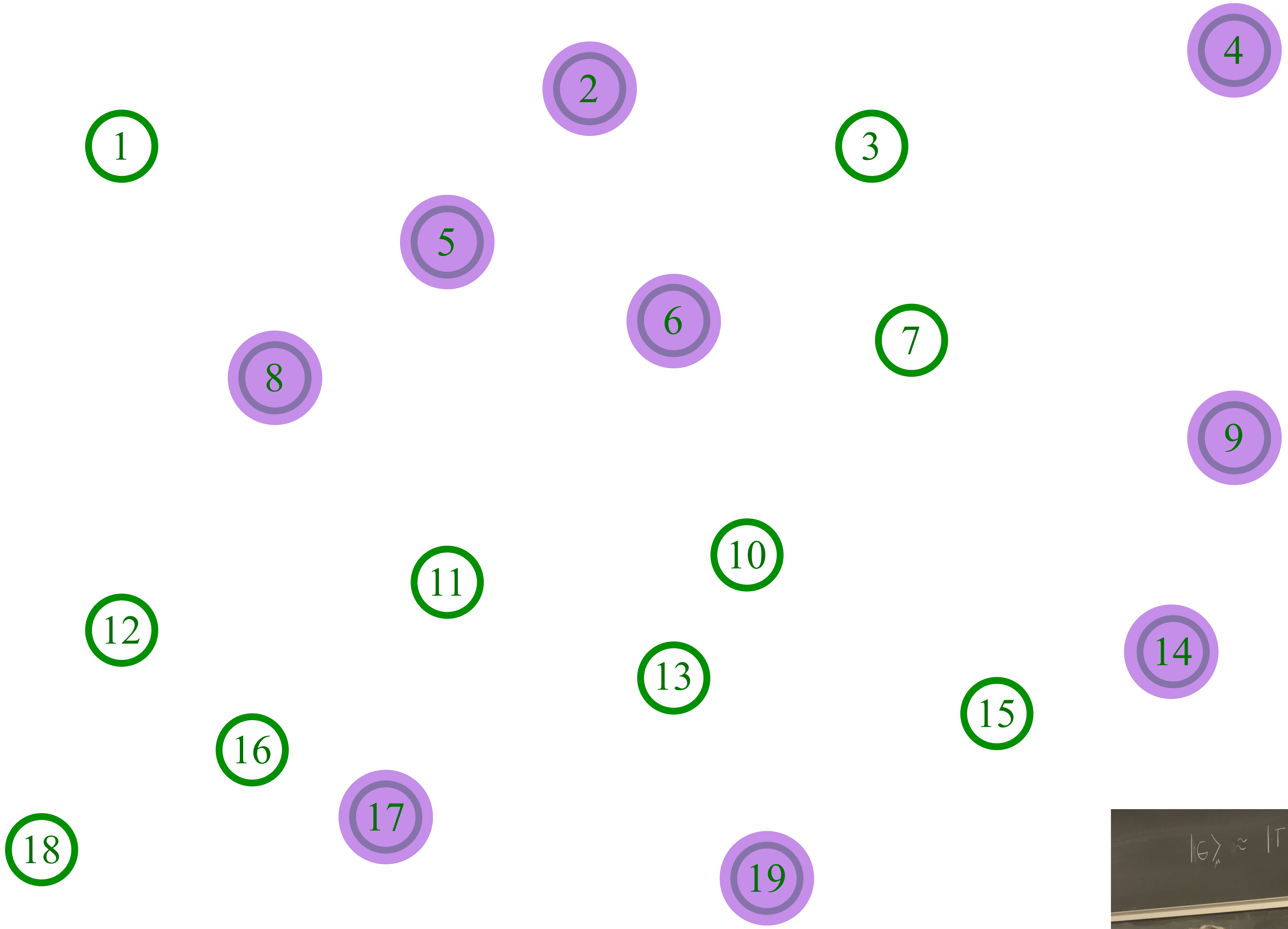
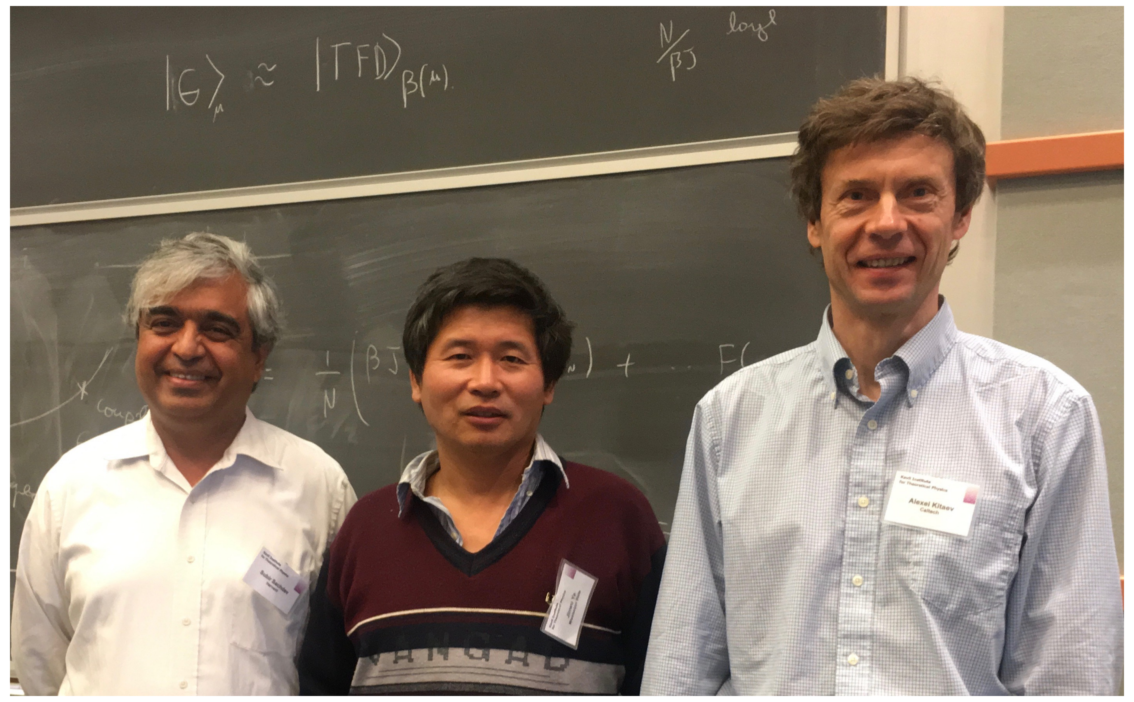


Entangle electrons pairwise randomly



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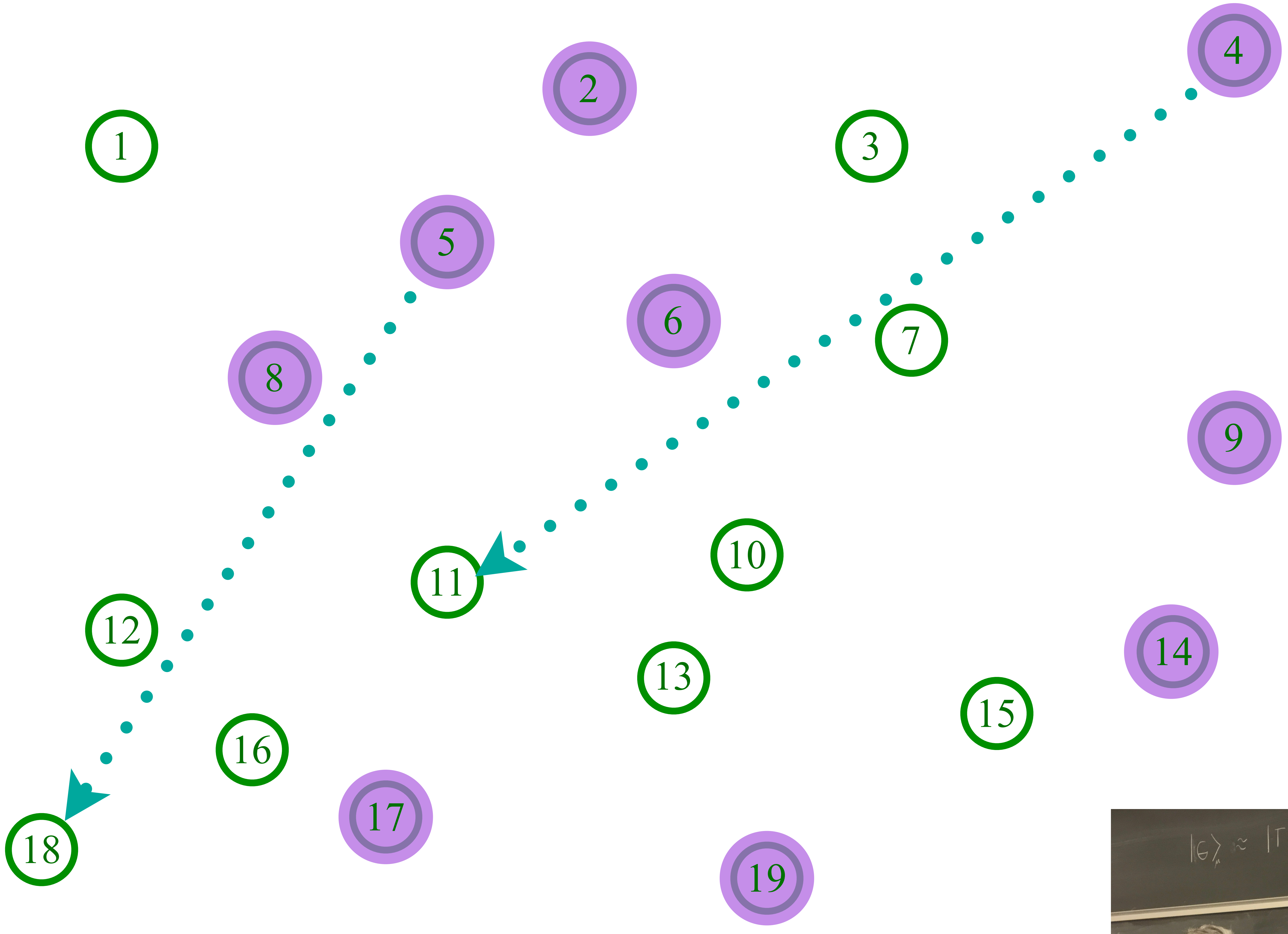
Sachdev, Ye (1993); Kitaev (2015)

$$U_{4,5;11,18}$$



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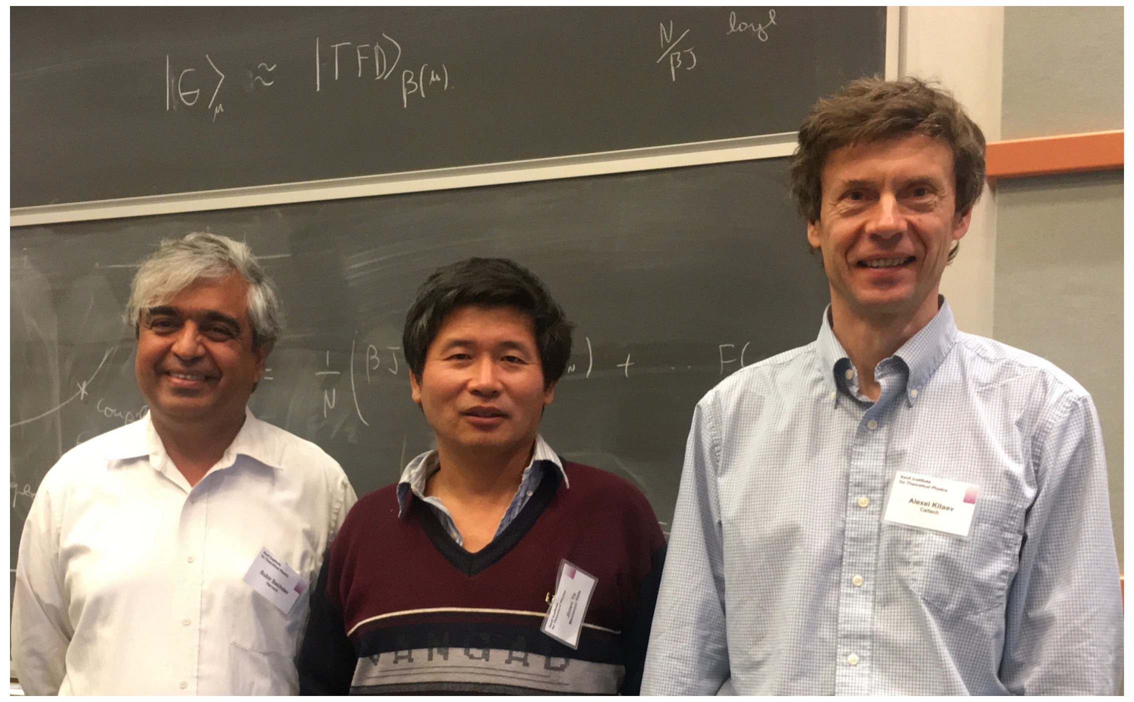

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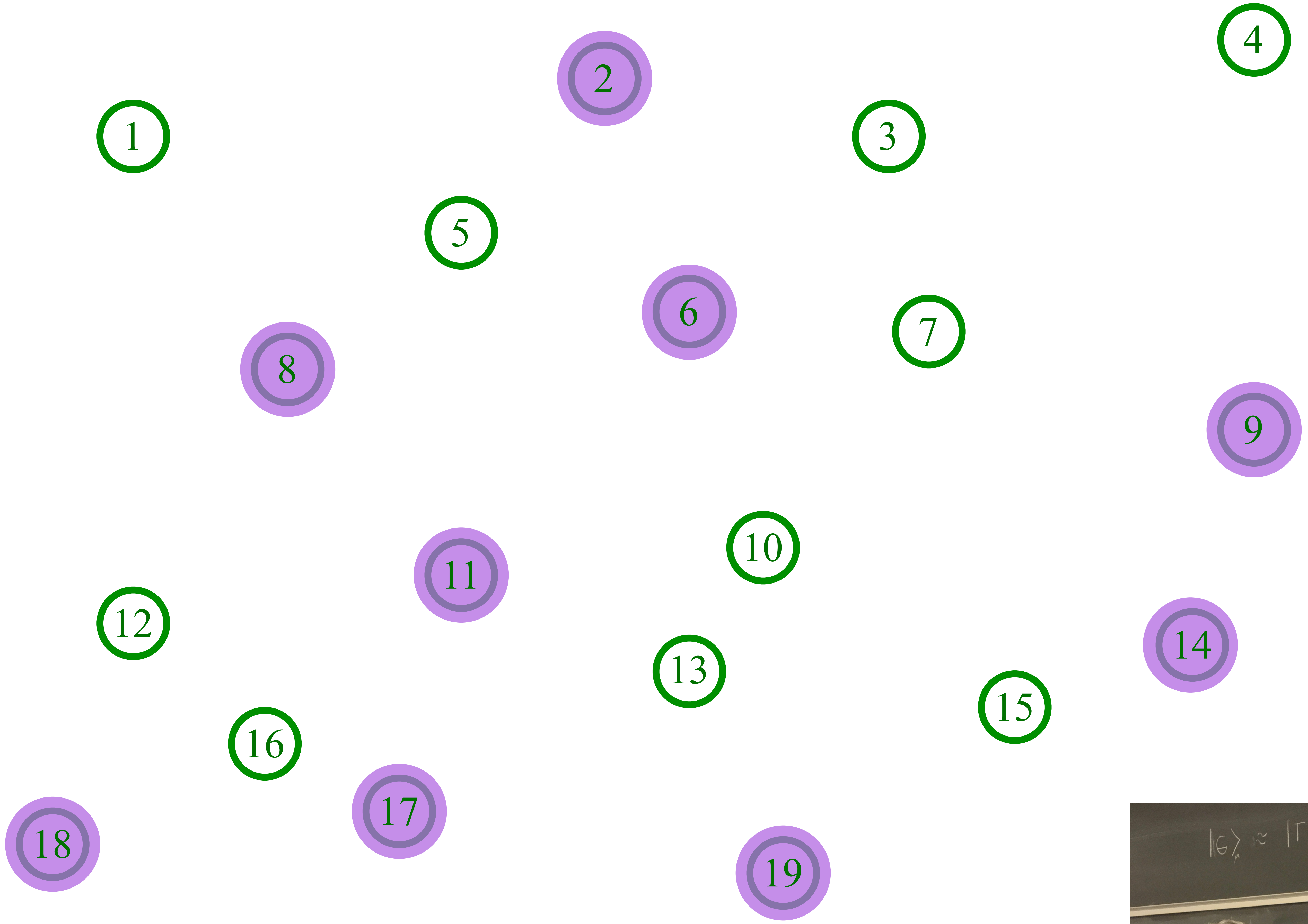

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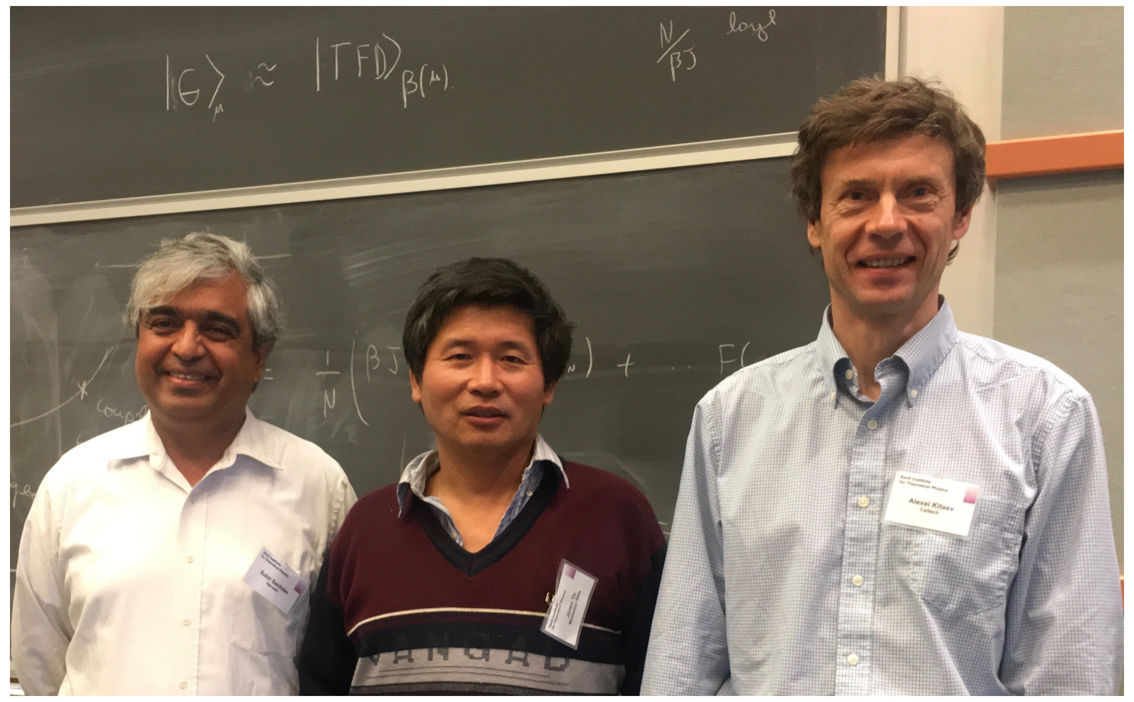

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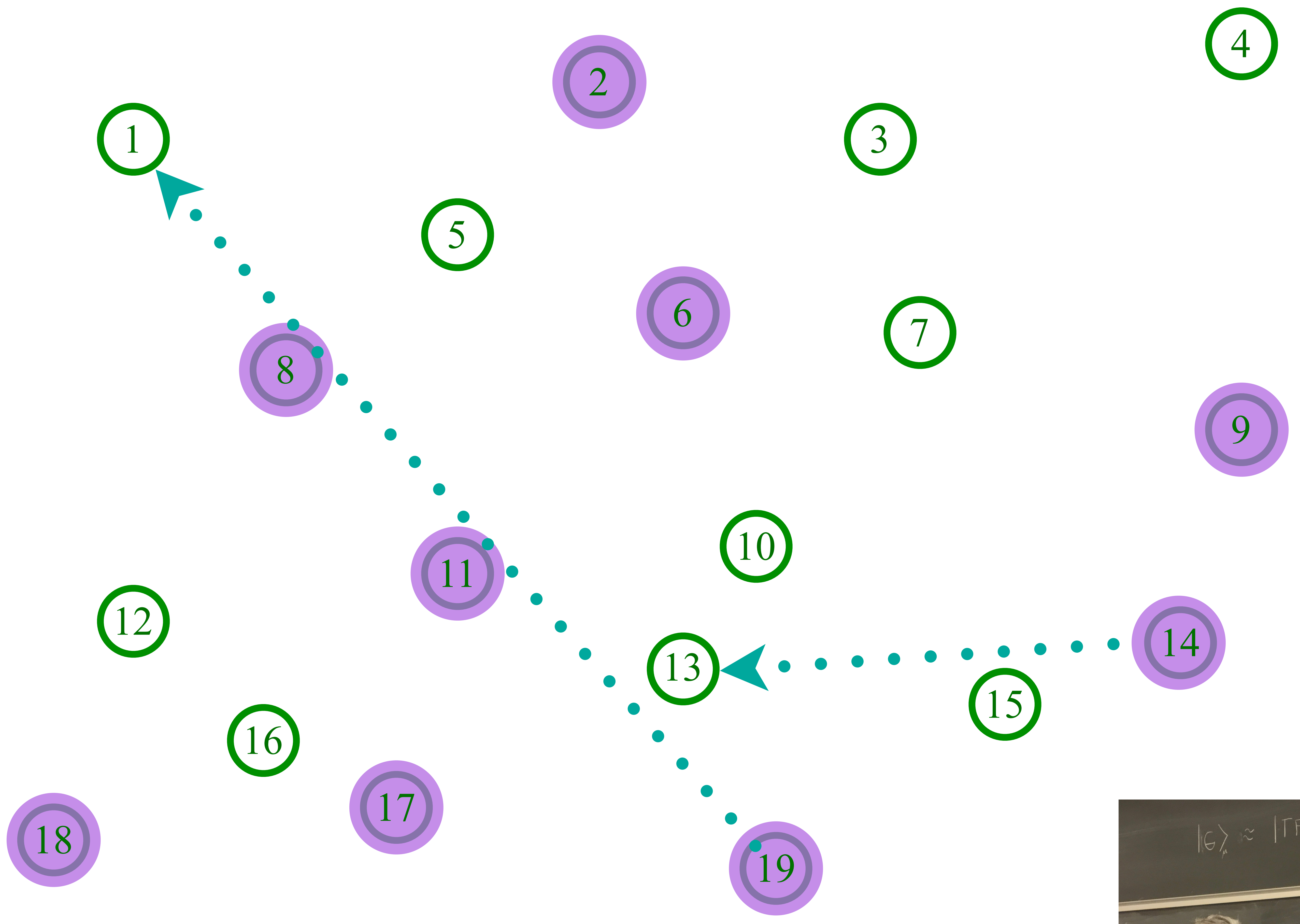
$$U_{14,19;1,13}$$



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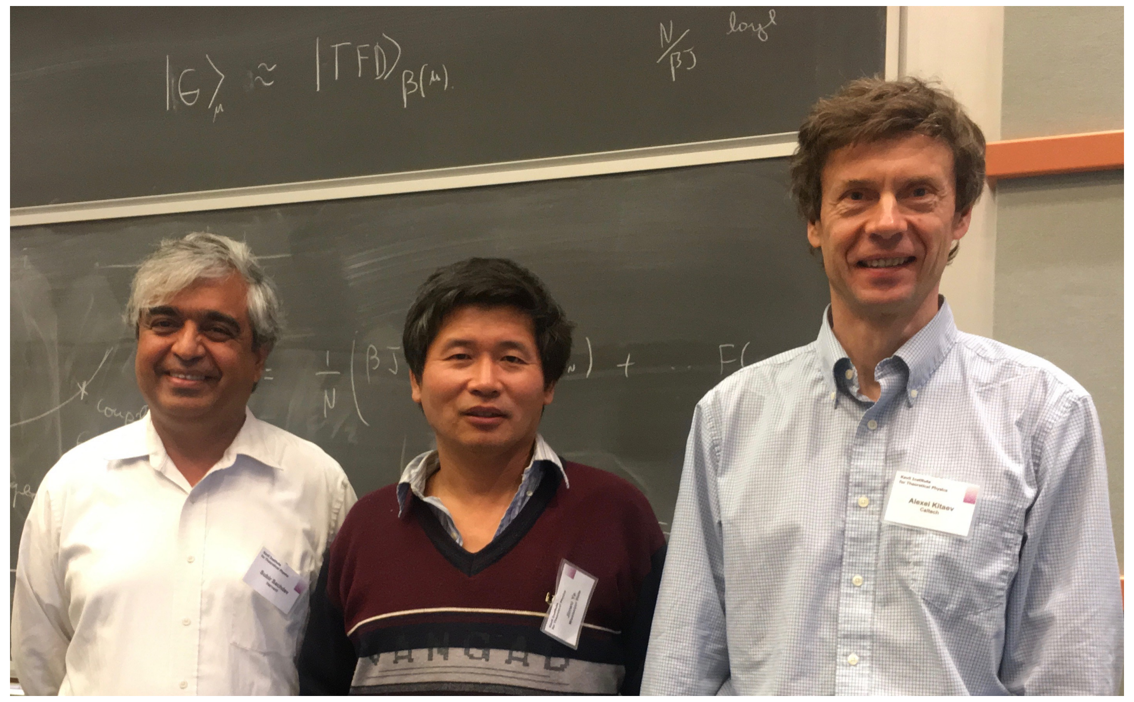

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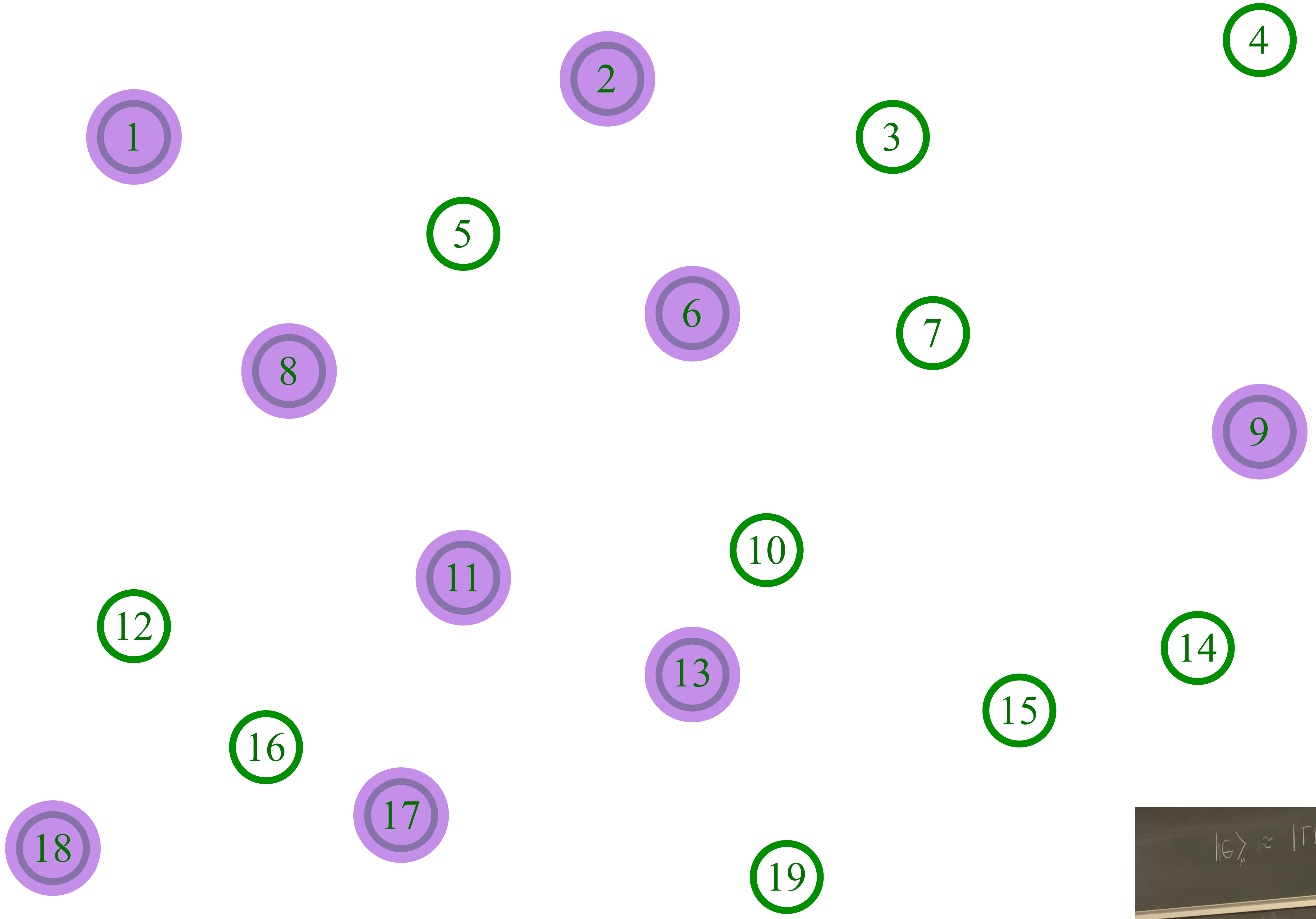
$$U_{14,19;1,13}$$



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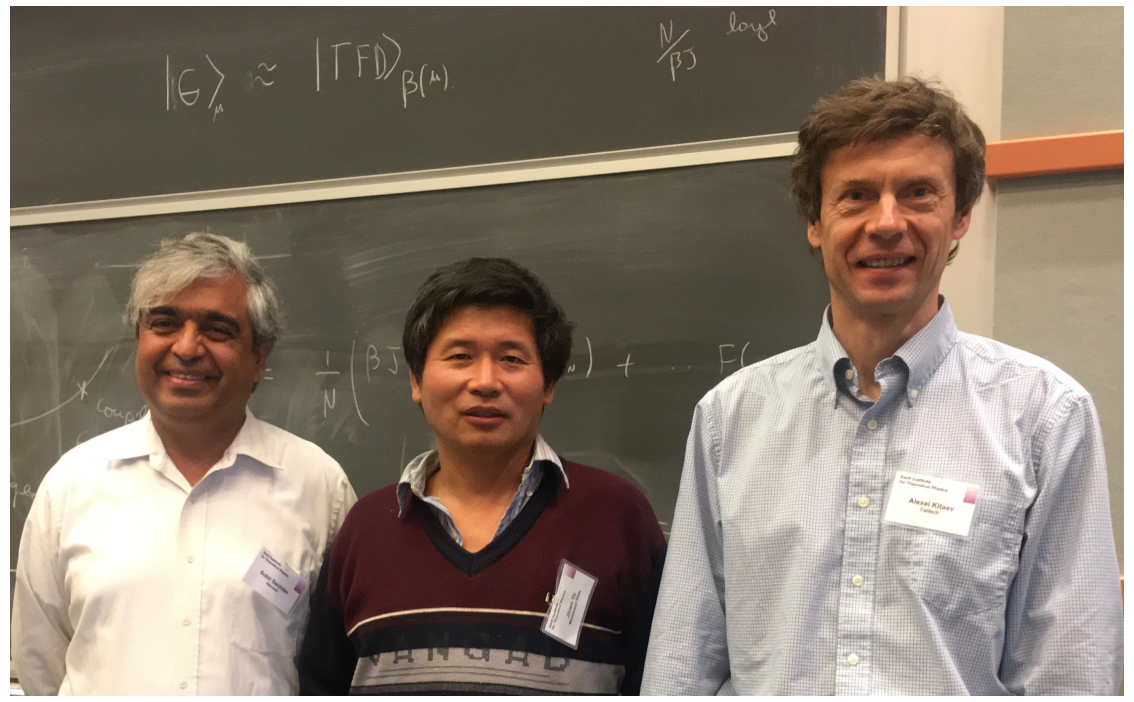

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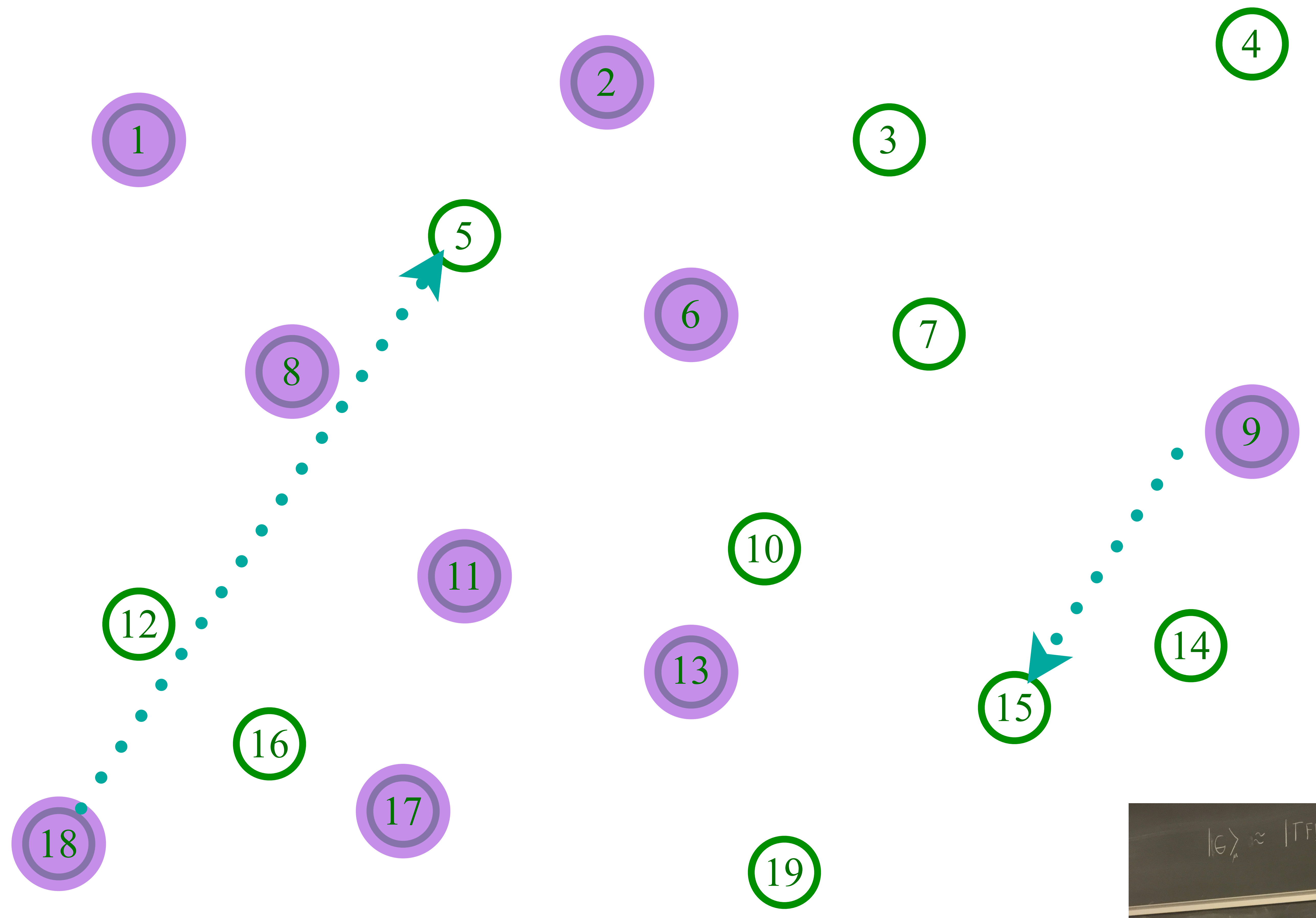
Sachdev, Ye (1993); Kitaev (2015)

$$U_{9,18;5,15}$$



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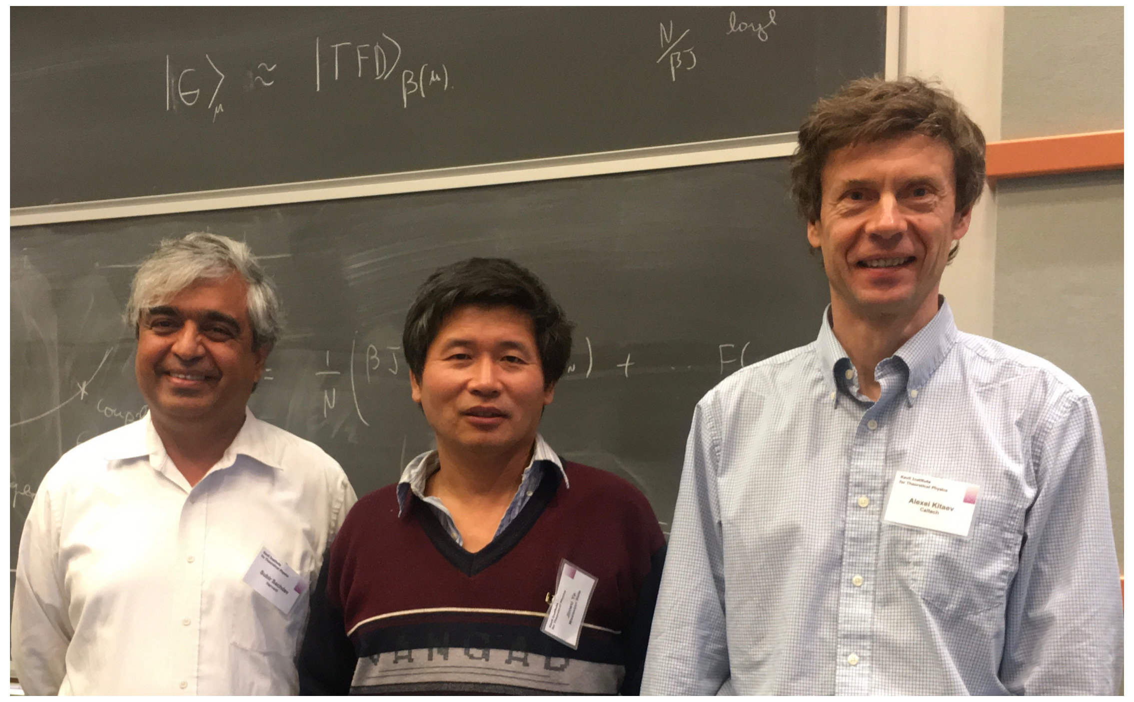

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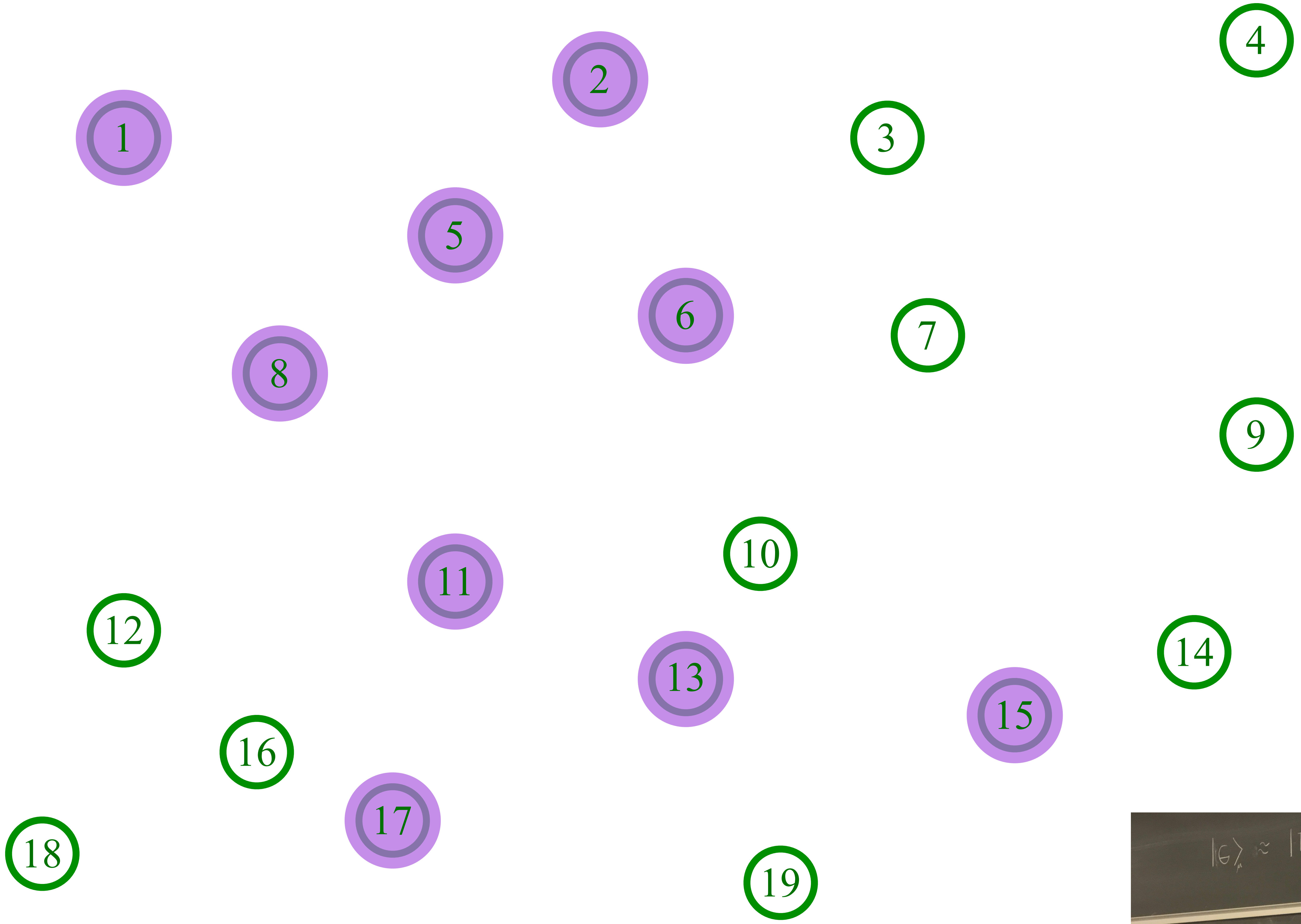

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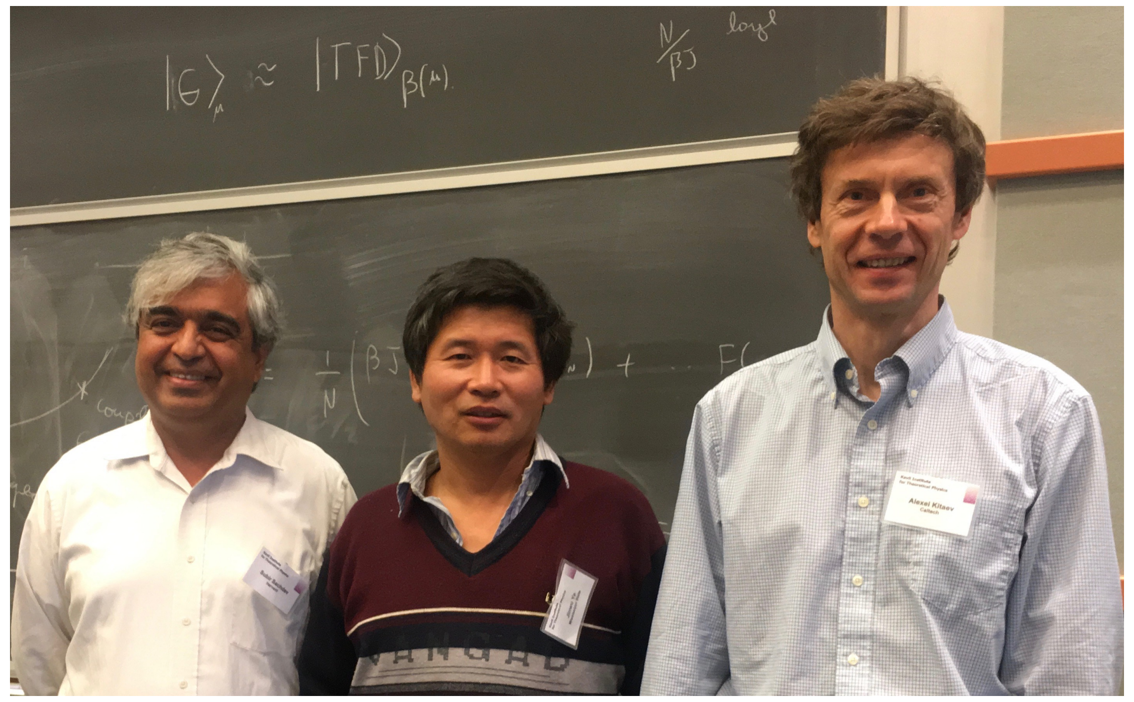

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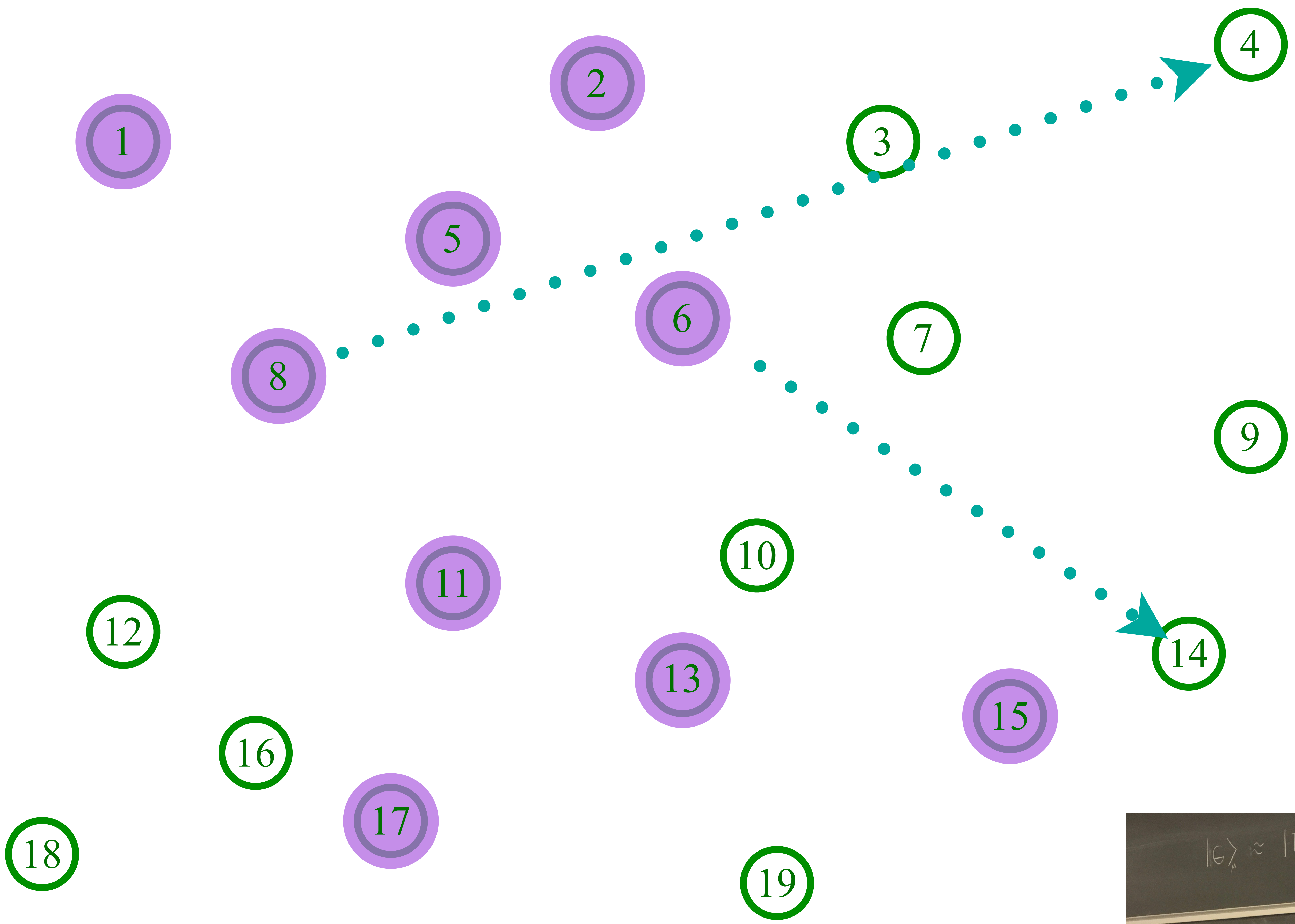
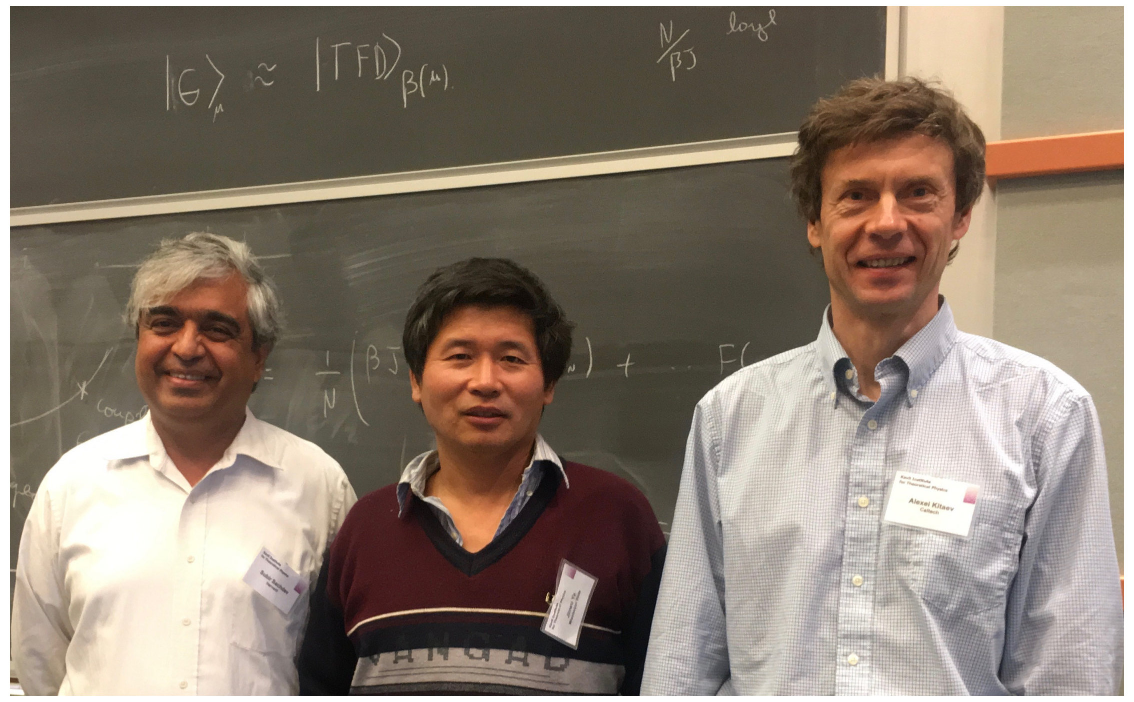
Sachdev, Ye (1993); Kitaev (2015)

$U_{6,8;4,14}$



Entangle electrons pairwise randomly



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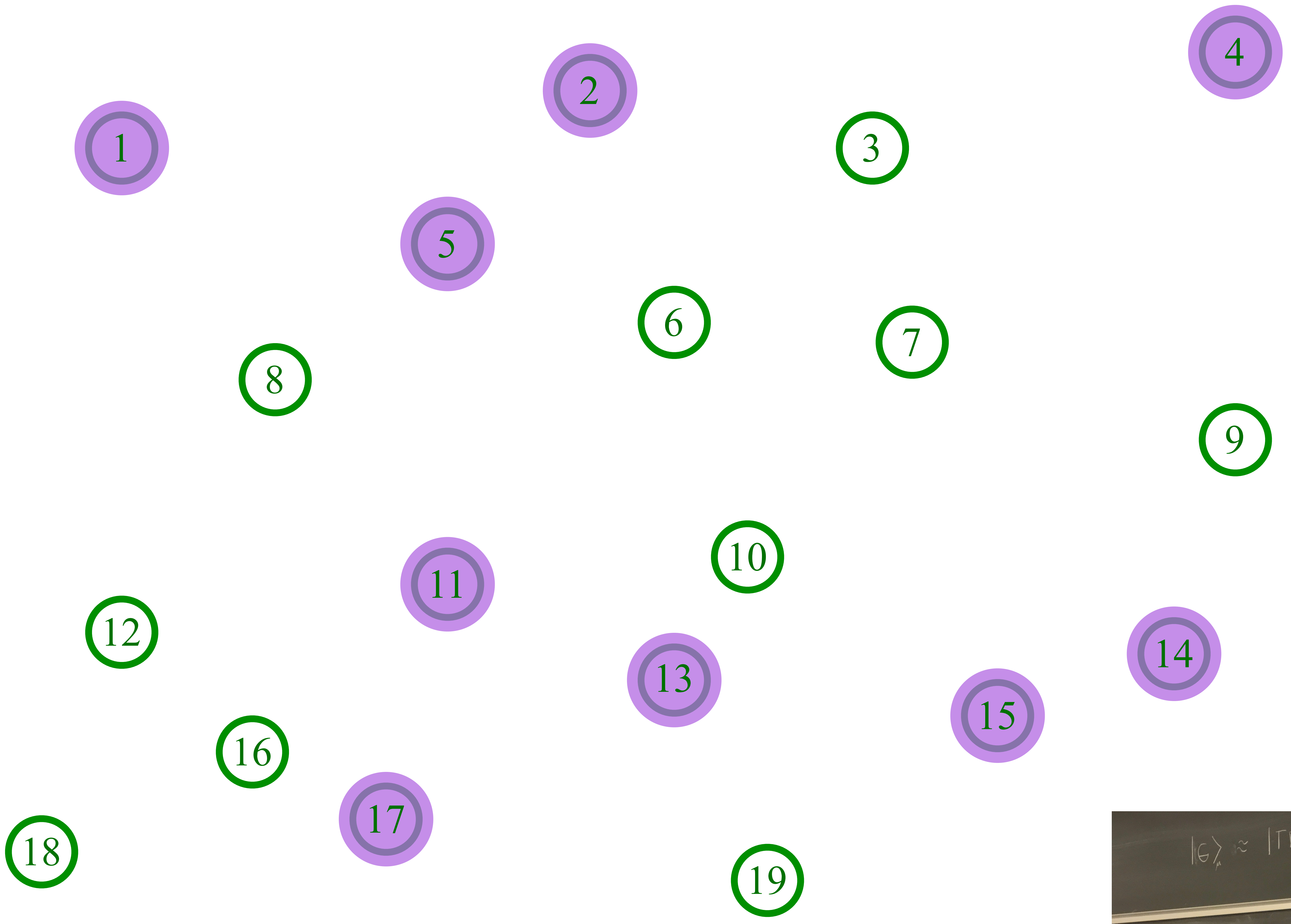

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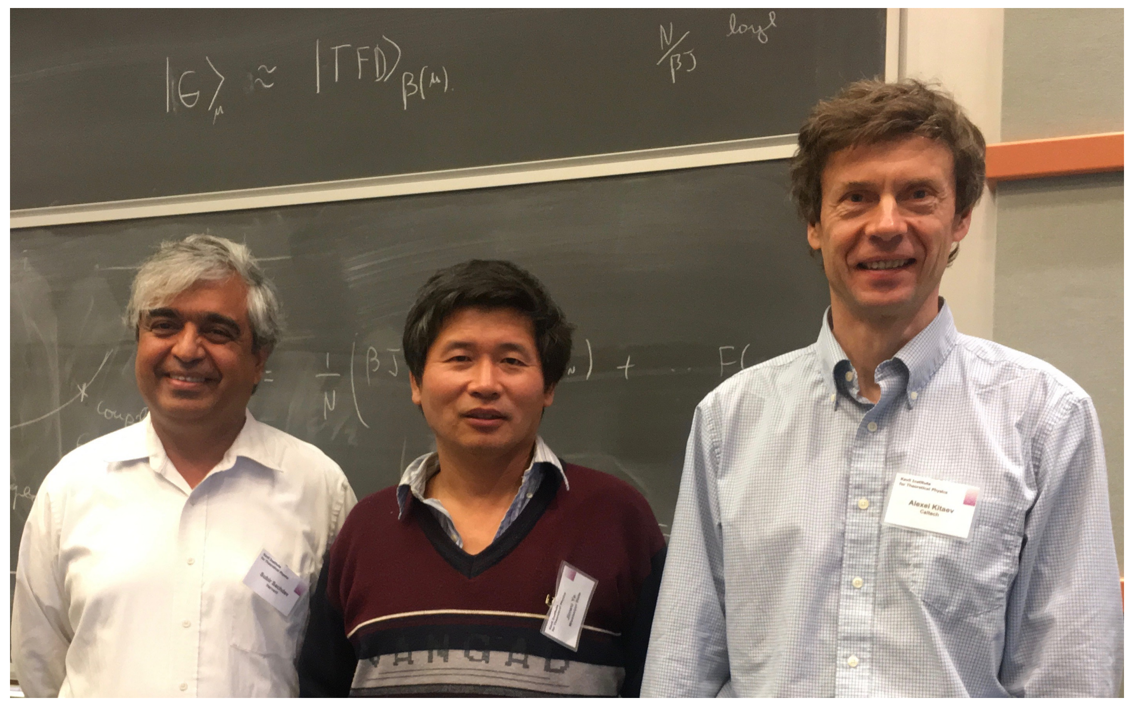

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle quantum entanglement.

No quasiparticles: yields a metal in which current is carried not by individual electrons, but by an entangled "quantum soup"

The SYK model

Consequences of emergent time-reparameterization and conformal symmetries in low-energy theory in 0+1 spacetime dimensions:

1. Planckian dynamics!

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right) \text{ independent of } U.$$

No bosons, fermions, anyons ...

A. Georges, O. Parcollet, and S. Sachdev (**GPS**), Physical Review B **63**, 134406 (2001)

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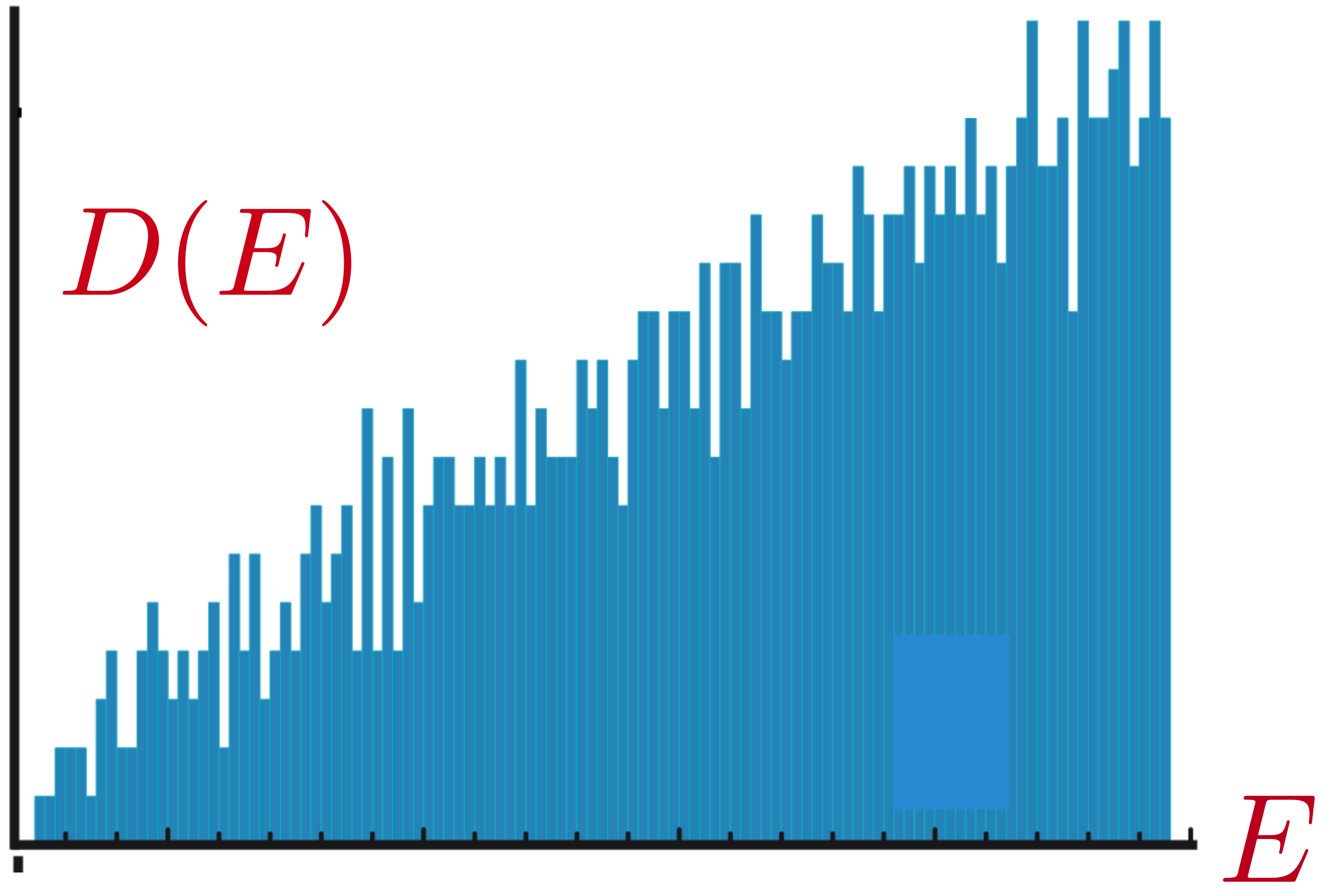
$$\lim_{T\to 0}\lim_{N\to\infty}\frac{1}{N}S(T) = s_0 \quad , \quad D(E\to 0) = e^{N s_0} f_{\text{smooth}}(E)$$

$$s_0 = 0.4648476991708051074 9.... \text{ for } \mathcal{Q} = 1/2.$$

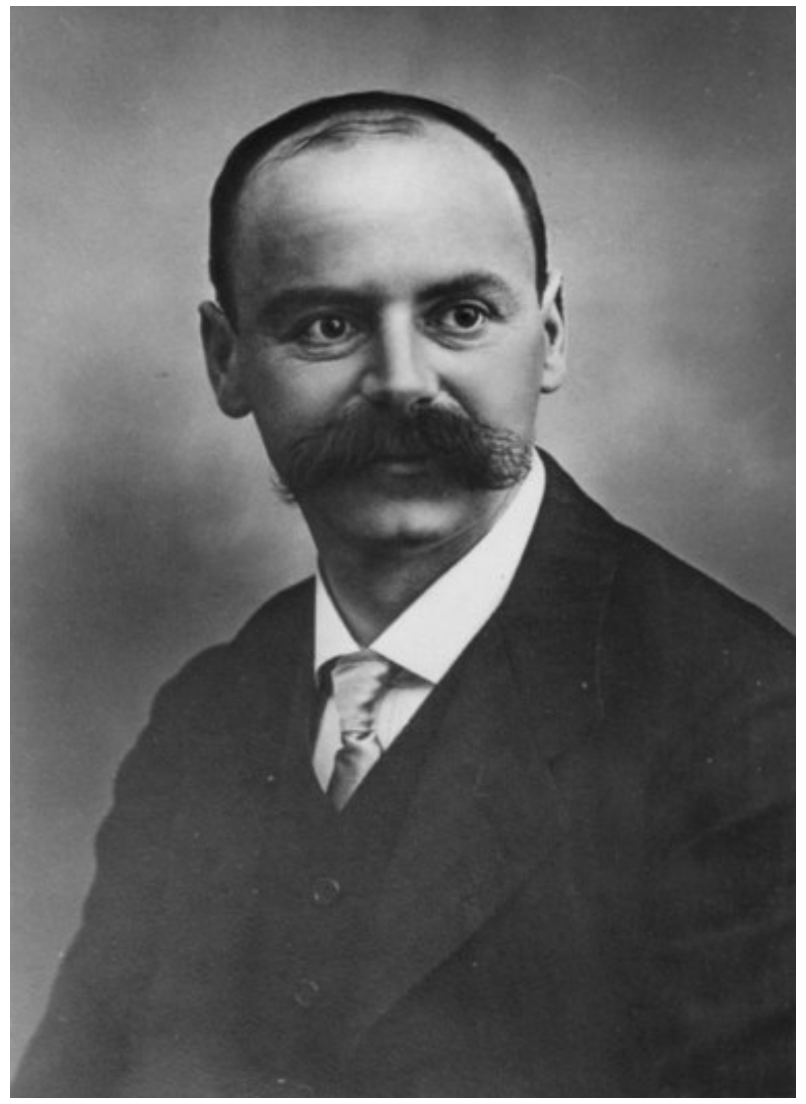


A. Georges, O. Parcollet, and S. Sachdev (**GPS**), Physical Review B **63**, 134406 (2001)

From
the SYK model
to
black holes

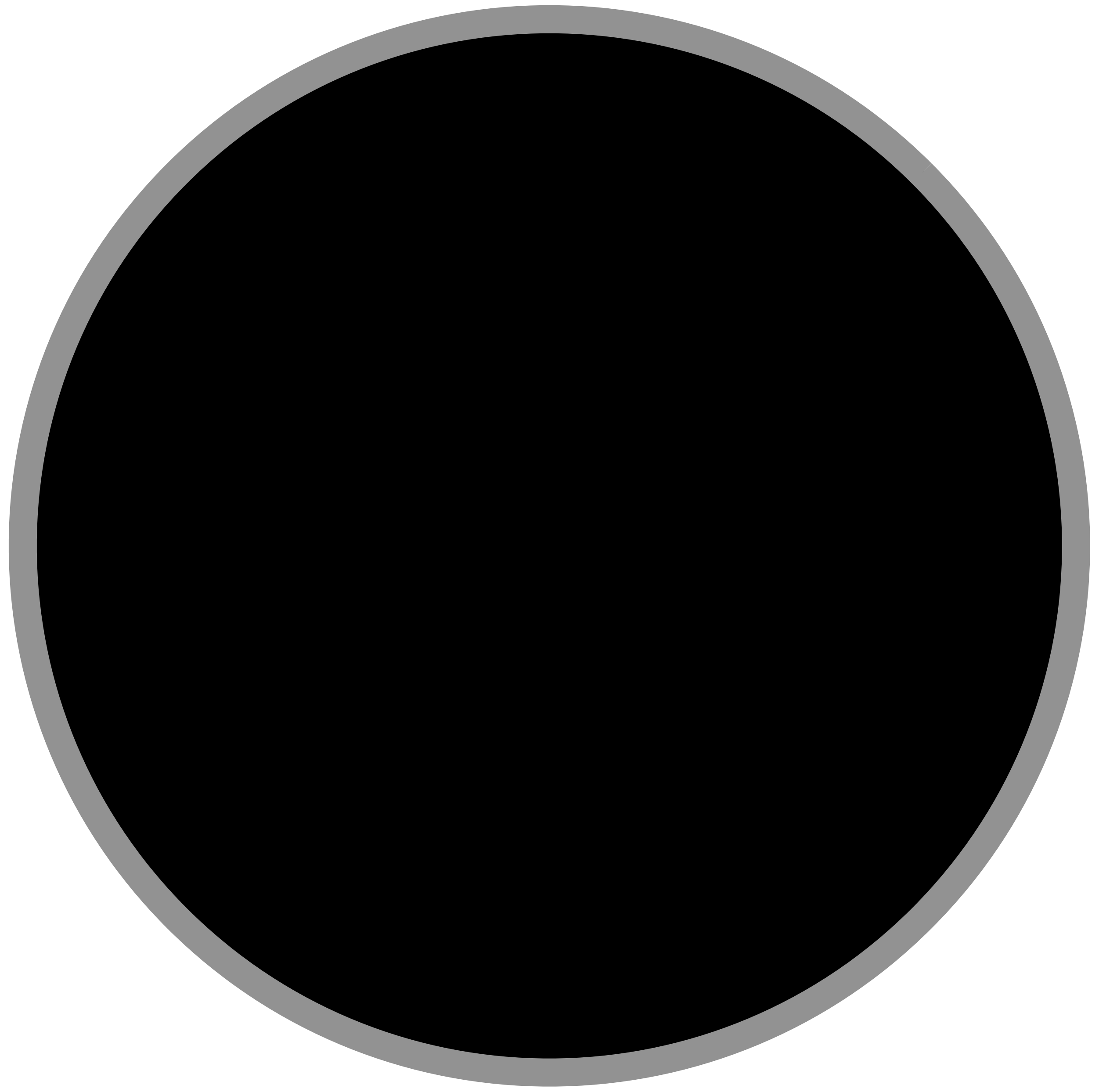
Black Holes

Objects so dense that light is gravitationally bound to them.



Karl Schwarzschild (1916)

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, $R \approx 9\,mm$!

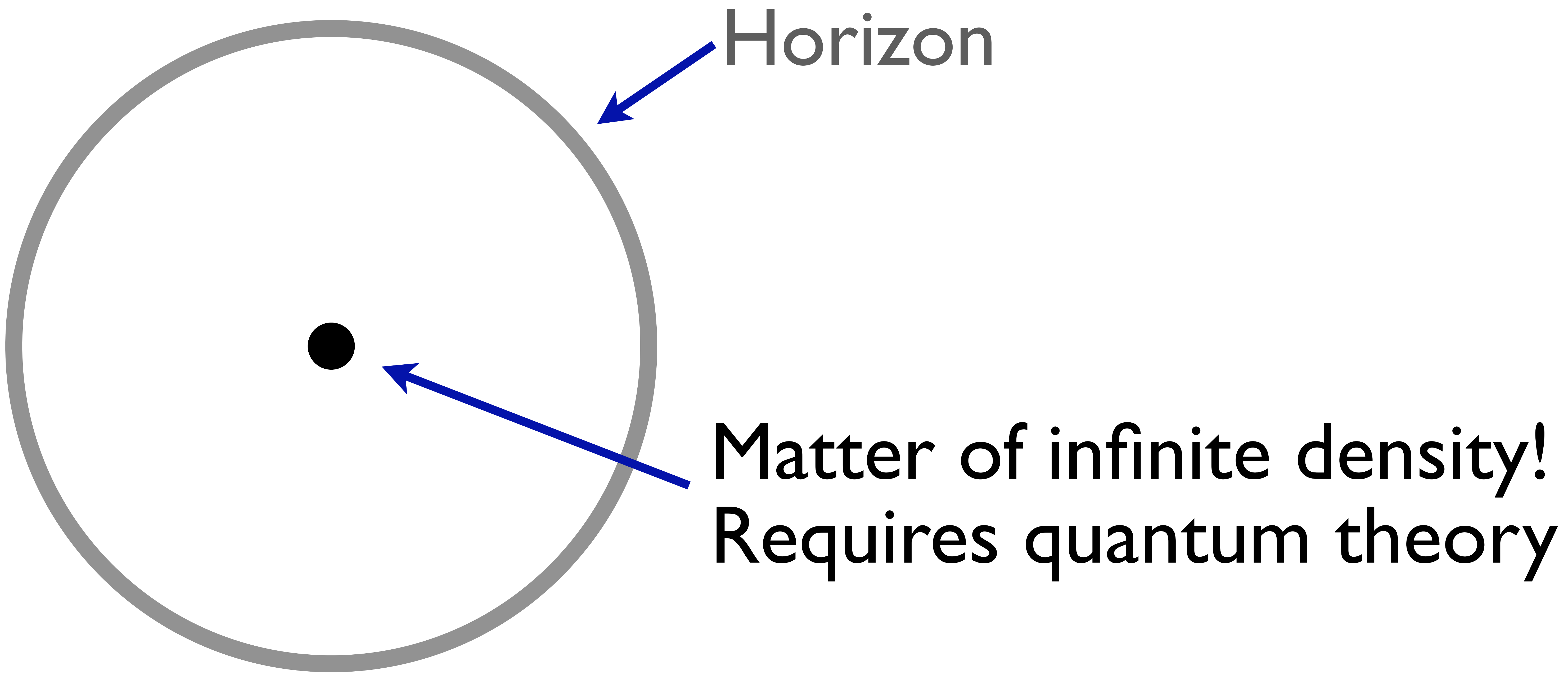
The supermassive black hole lurking at the heart of the Milky Way – Sagittarius A* contains about 4.3 million solar masses

$$R = 1.3 \times 10^{11}\mathrm{m}$$
$$\approx \text{earth's orbit}$$

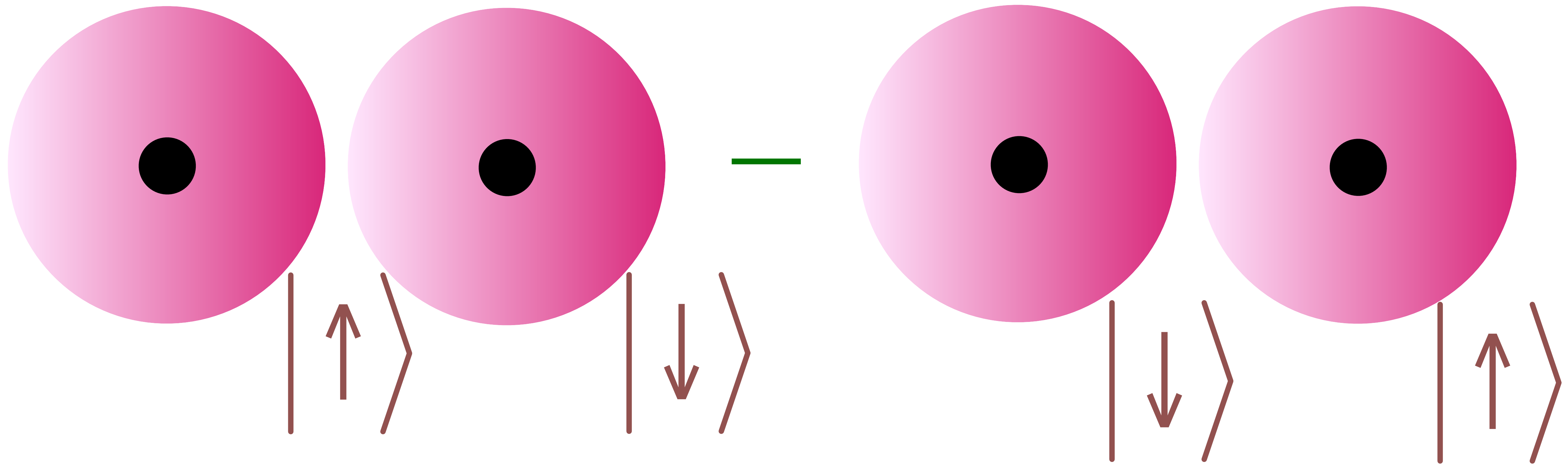
Event Horizon Telescope
May 12, 2022

What is inside a black hole ???

In Einstein's theory, all the matter in a black hole collapses to a singularity at the center of the black hole.



Quantum Entanglement across a black hole horizon



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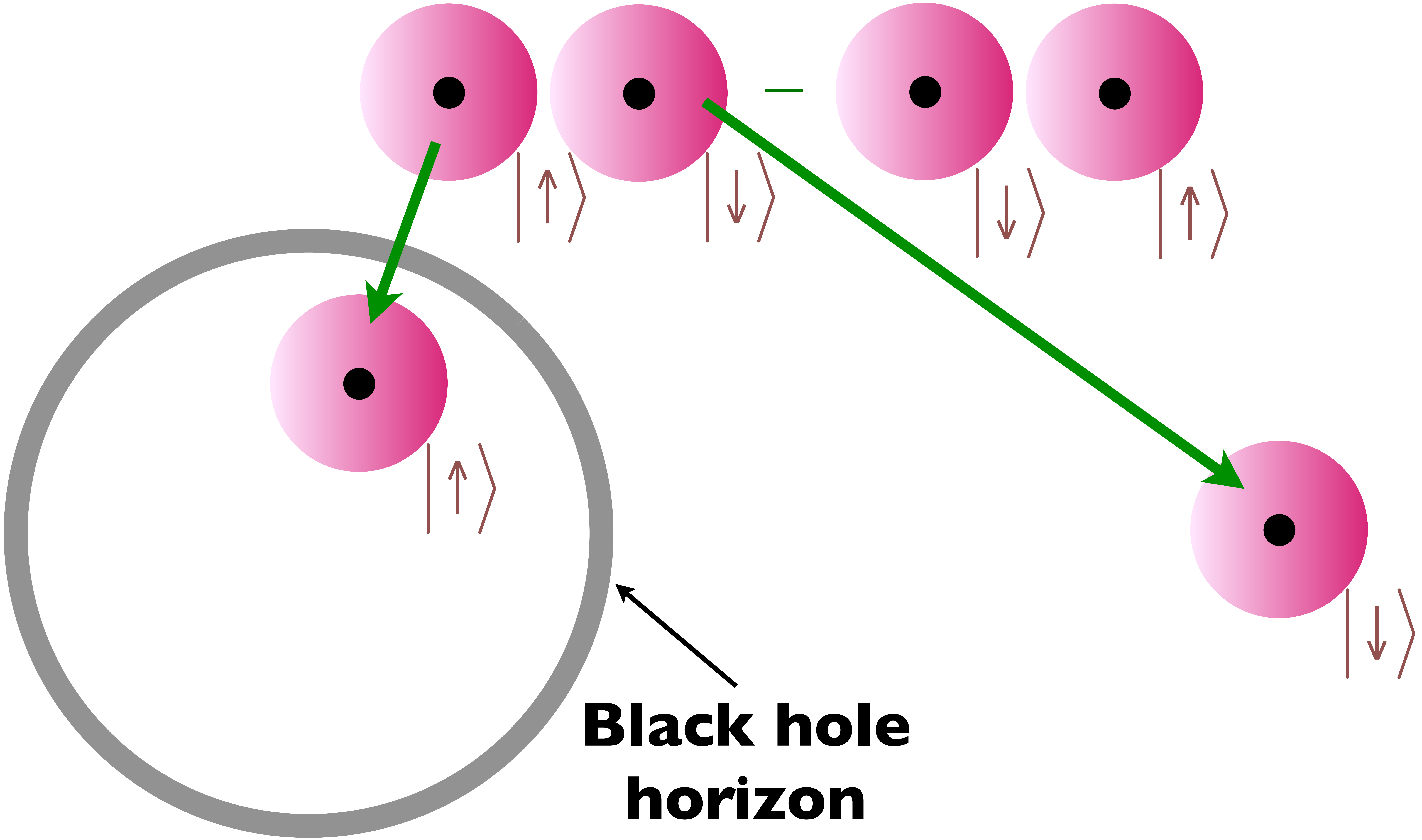

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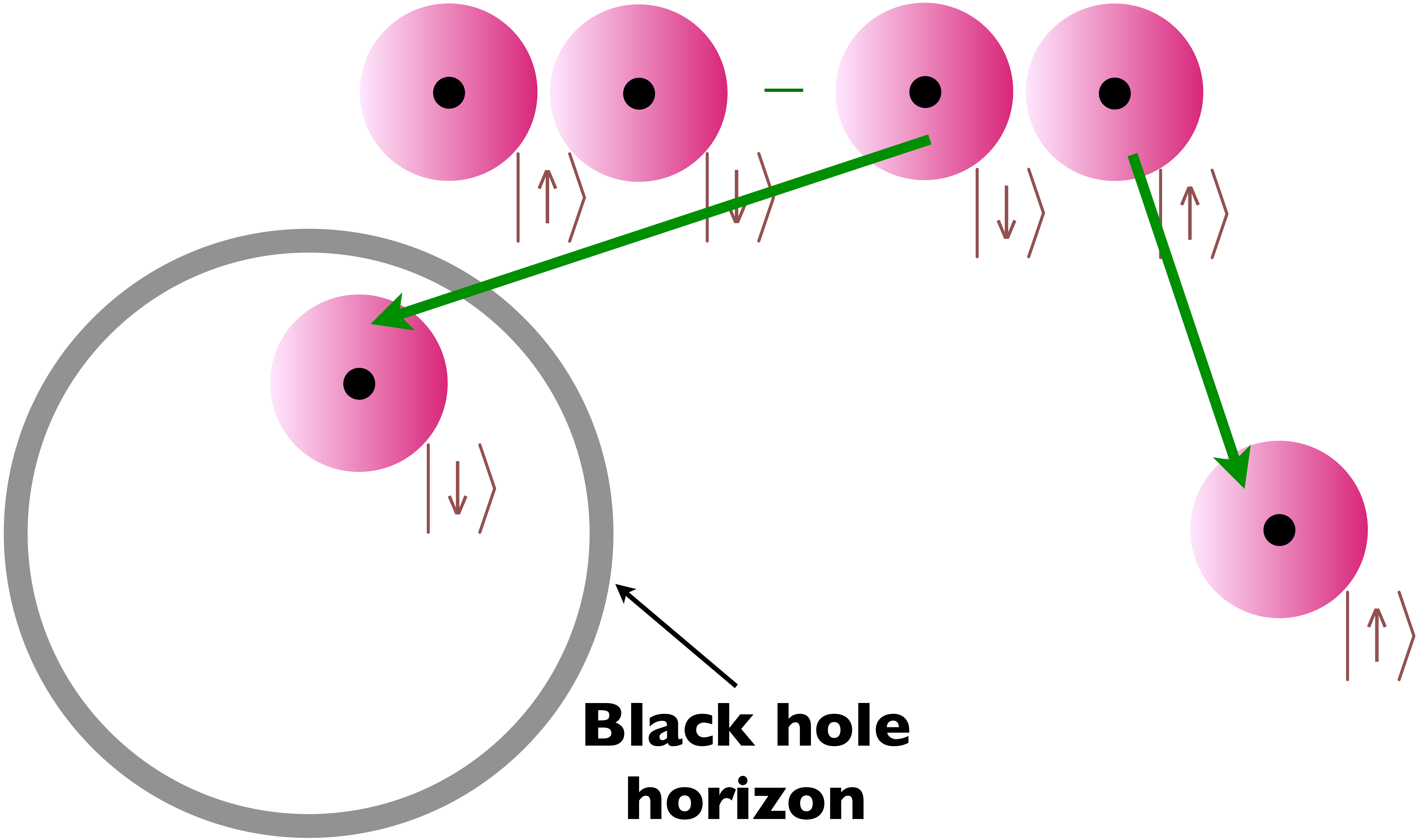
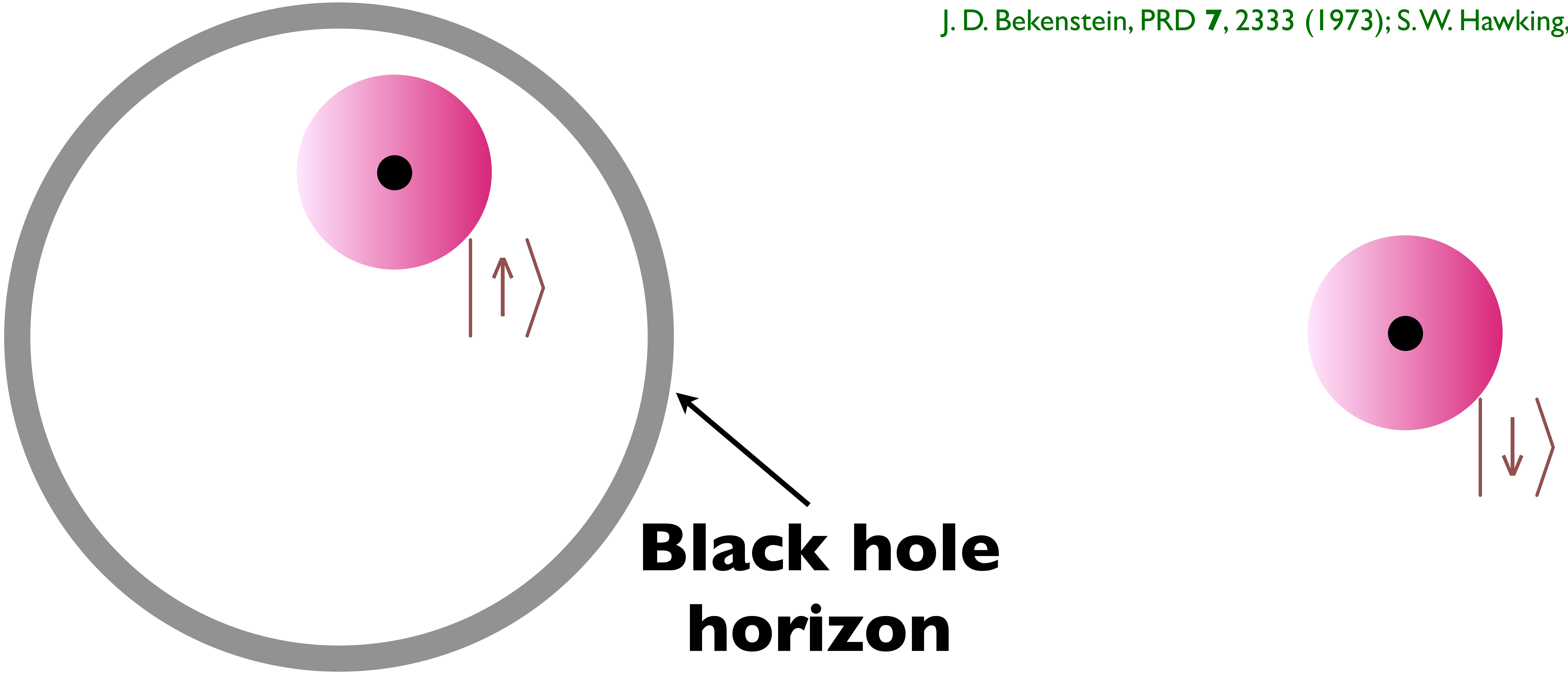


Quantum Entanglement across a black hole horizon

Bekenstein, Hawking: Black holes have a temperature and an entropy!

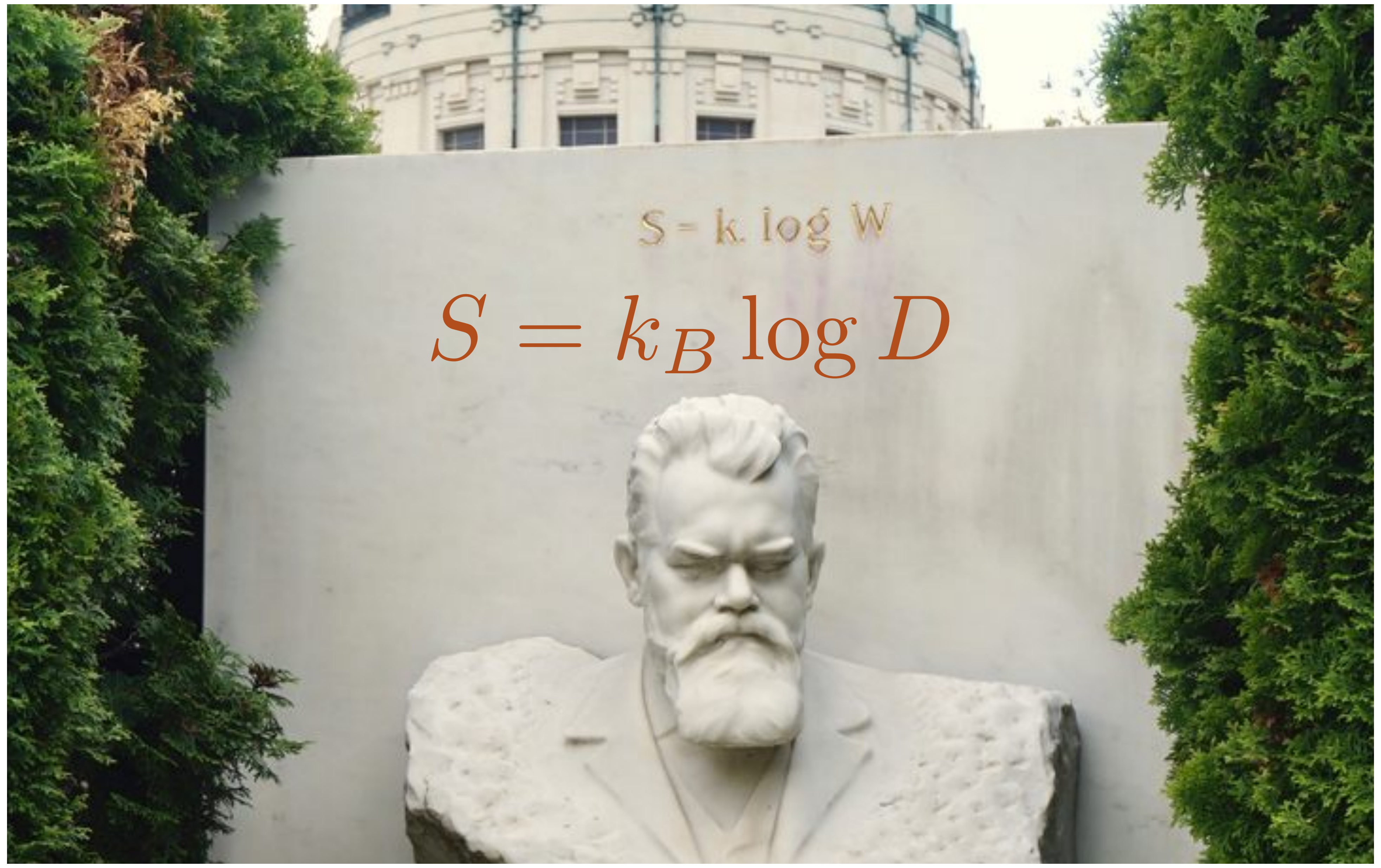
To an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.

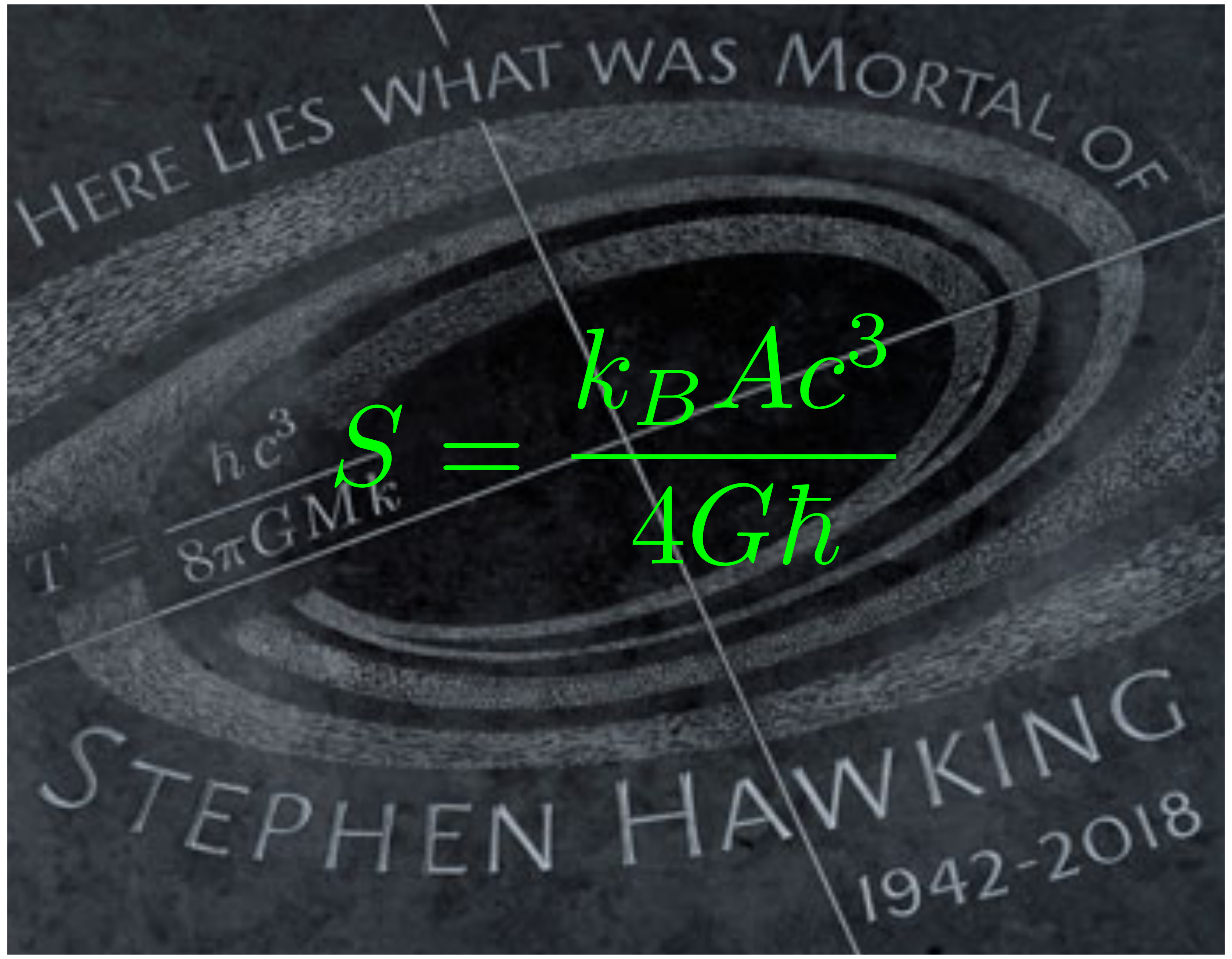
J. D. Bekenstein, PRD **7**, 2333 (1973); S.W. Hawking, Nature **248**, 30 (1974)



Quantum Black Holes

- Can we find a quantum theory for the collapsed matter at the center of the black hole, whose *density of quantum states* $D(E)$ [the quantum analog of Boltzmann's W] matches Bekenstein-Hawking entropy, in accordance with Boltzmann's principles of statistical mechanics, $S(E) = k_B \log D(E)$?





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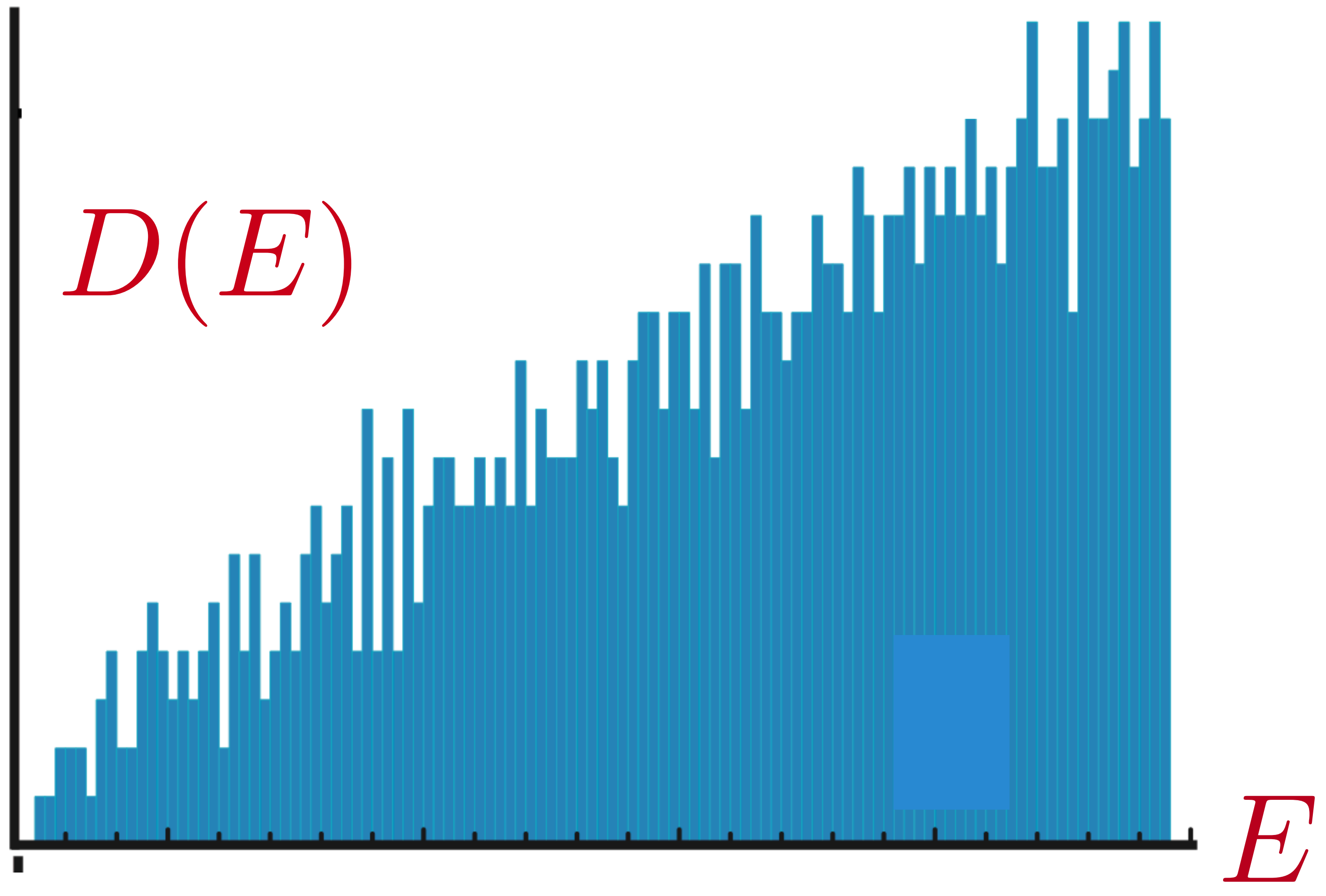

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Connections between the SYK model and black holes

- Black hole 'ring-down' or 'quasinormal mode damping' or 'chaos' times are Planckian $\sim \hbar/(k_B T)$

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

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  $S_{BH} = A_0 c^3/(4\hbar G)$ where $A_0 = 2GQ^2/c^4$ is the area of the charged black hole horizon at $T = 0$.

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  Also applies to rotating neutral black holes.

U. Moitra, S.K. Sake, S.P. Trivedi and V. Vishal, JHEP 11 (2019) 047.
D. Kapec, A. Sheta, A. Strominger and C. Toldo, PRL 133 (2024) 021601
M. Kolanowski, D. Marolf, I. Rakic, M. Rangamani and G.J. Turiaci, arXiv:2409.16248

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

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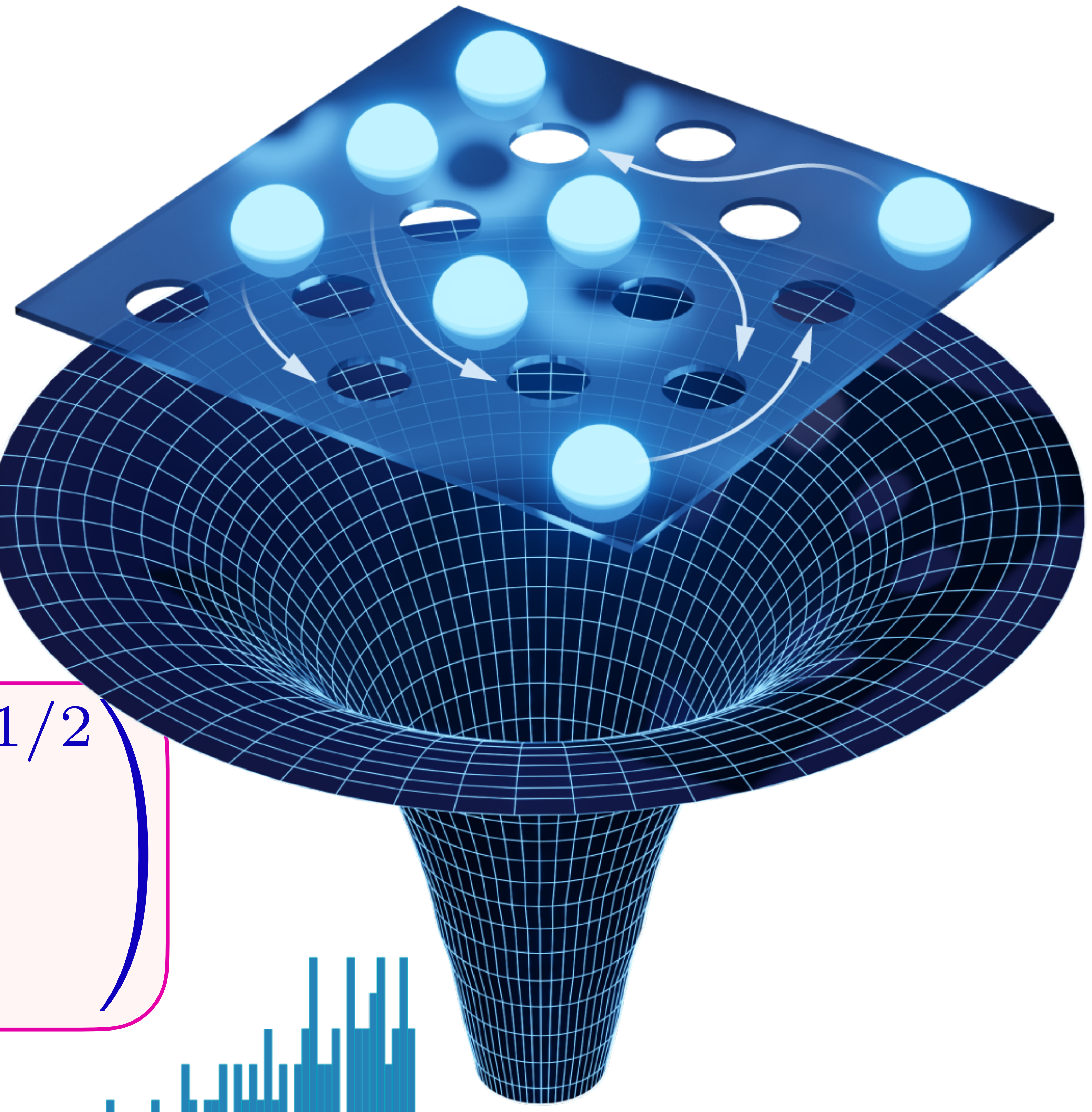
  Also applies to rotating neutral black holes.

- The example of the SYK model implies that S_{BH} is *not* realized by an exponentially large ground state degeneracy (as is the case in all earlier string-theoretic computations).

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

D(E) of charged black holes from the SYK model



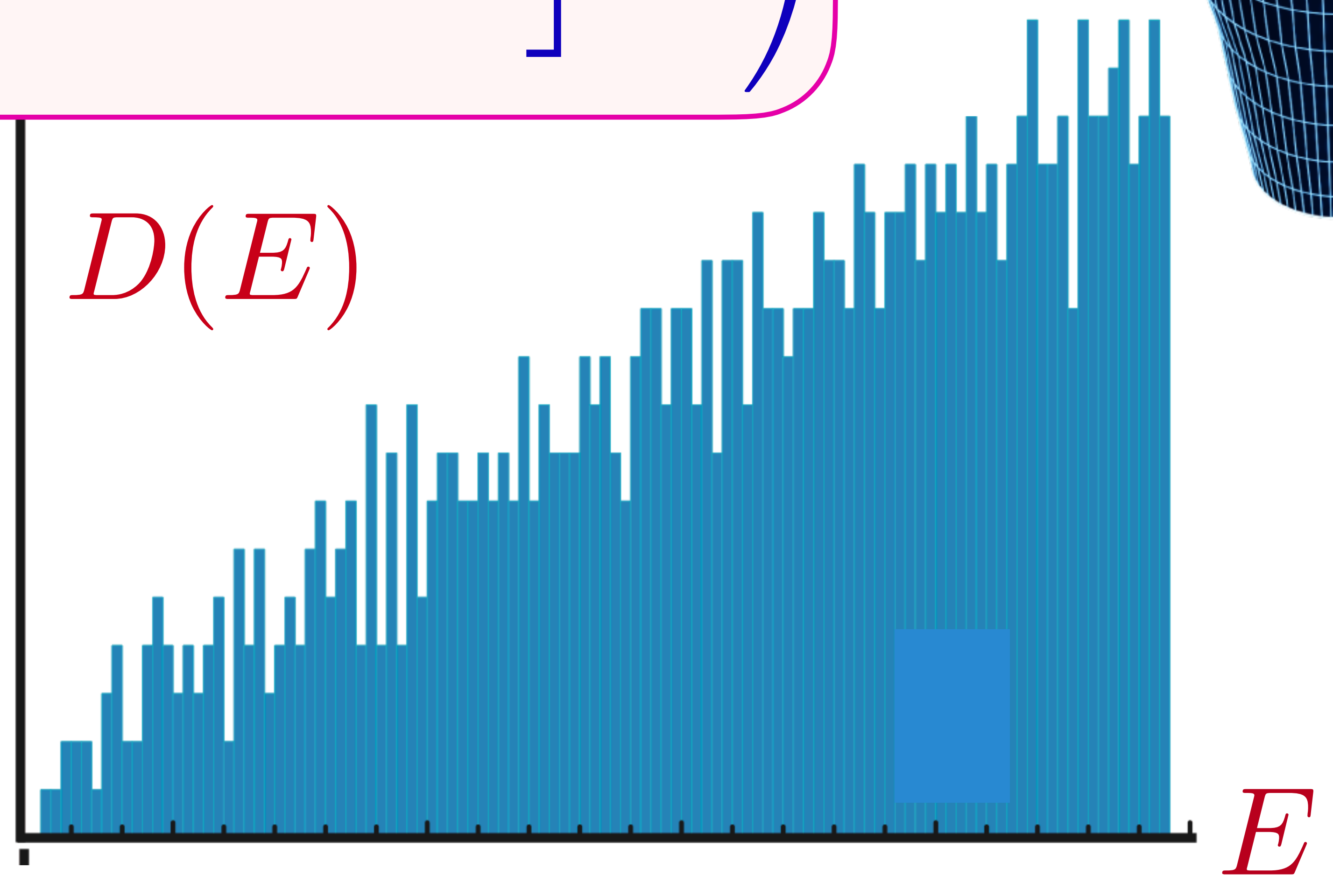
- For generic charged black holes in 3+1 dimensions with horizon area A_0 at $T = 0$ and fixed charge $\mathcal{Q}$ ($A_0 = 2G\mathcal{Q}^2/c^4$), the density of quantum states at small energy E is

Bekenstein-Hawking

$$D(E) \sim \left(\frac{A_0 c^3}{\hbar G}\right)^{-347/90} \exp\left(\frac{A_0 c^3}{4\hbar G}\right) \sinh\left(\left[\frac{\sqrt{\pi} {A_0}^{3/2} c^2}{\hbar^2 G} E\right]^{1/2}\right)$$

Iliesiu, Murthy, Turiaci (2022)

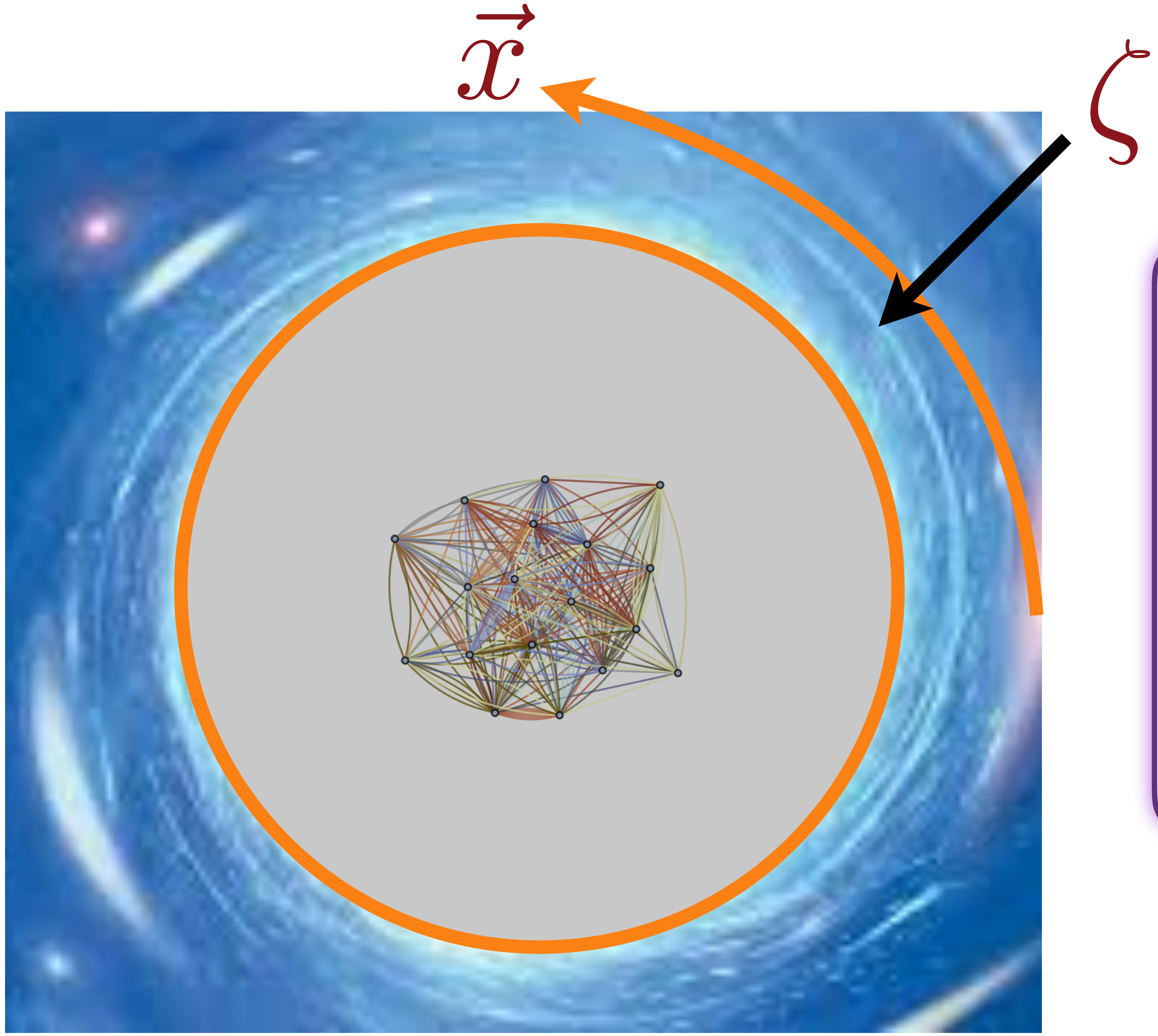
$f_{\mathrm{smooth}}(E)$: developments from the SYK model



Similar remarks apply to rotating neutral black holes.

D. Chowdhury, A. Georges, O. Parcollet, and S. S., Rev. Mod. Phys. **94**, 035004 (2022)

Quantum simulation of charged black holes by the SYK model



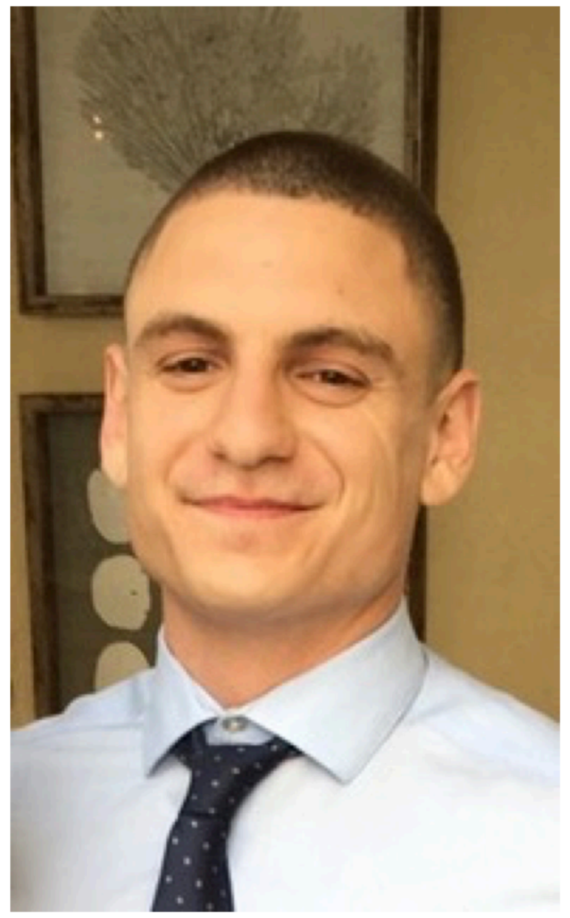
The SYK model simulates the low energy properties of the interior of the black hole for an outside observer in ζ-τ co-ordinates.

From the SYK model to the universal 2d-YSYK theory of strange metals

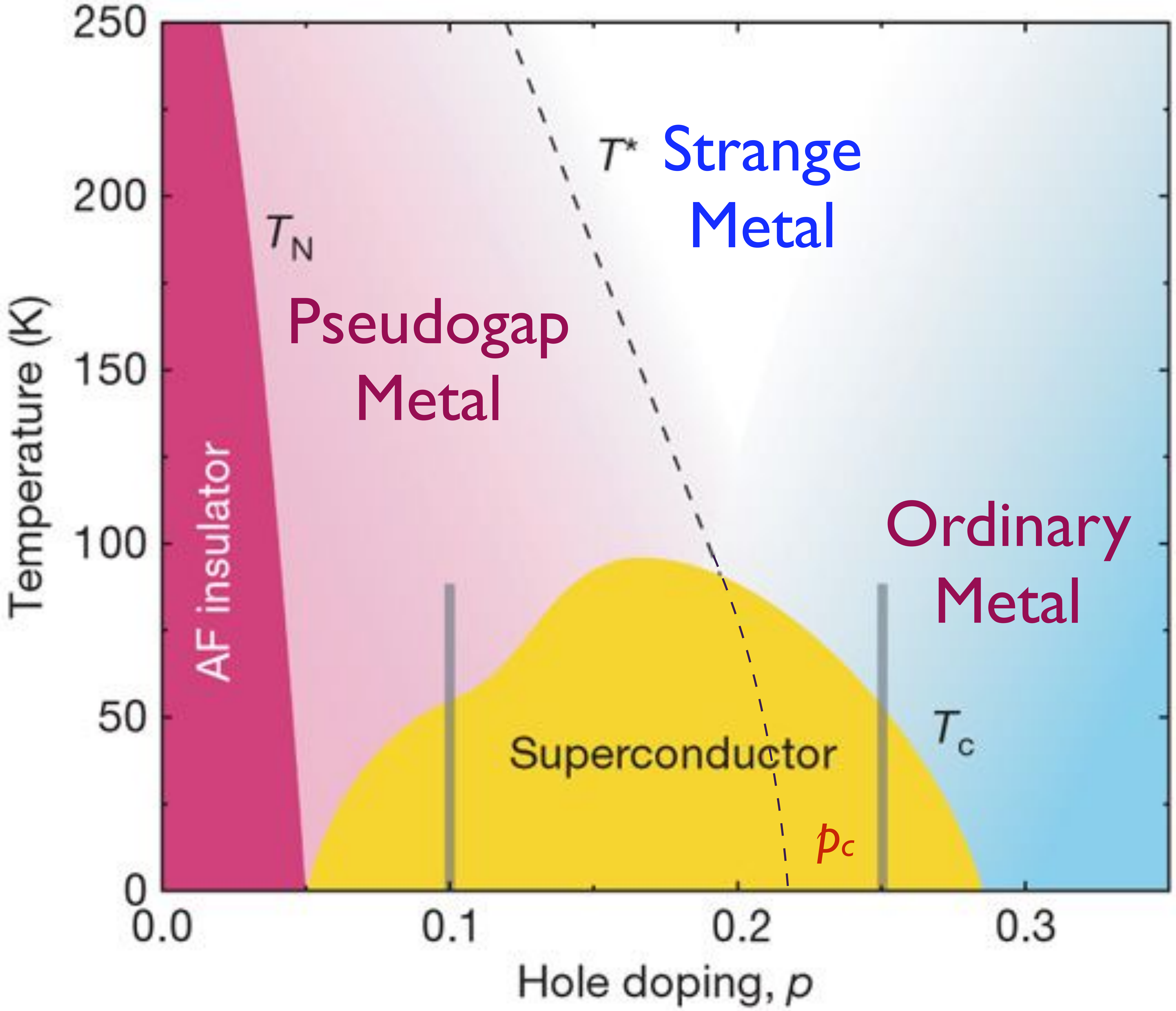
Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

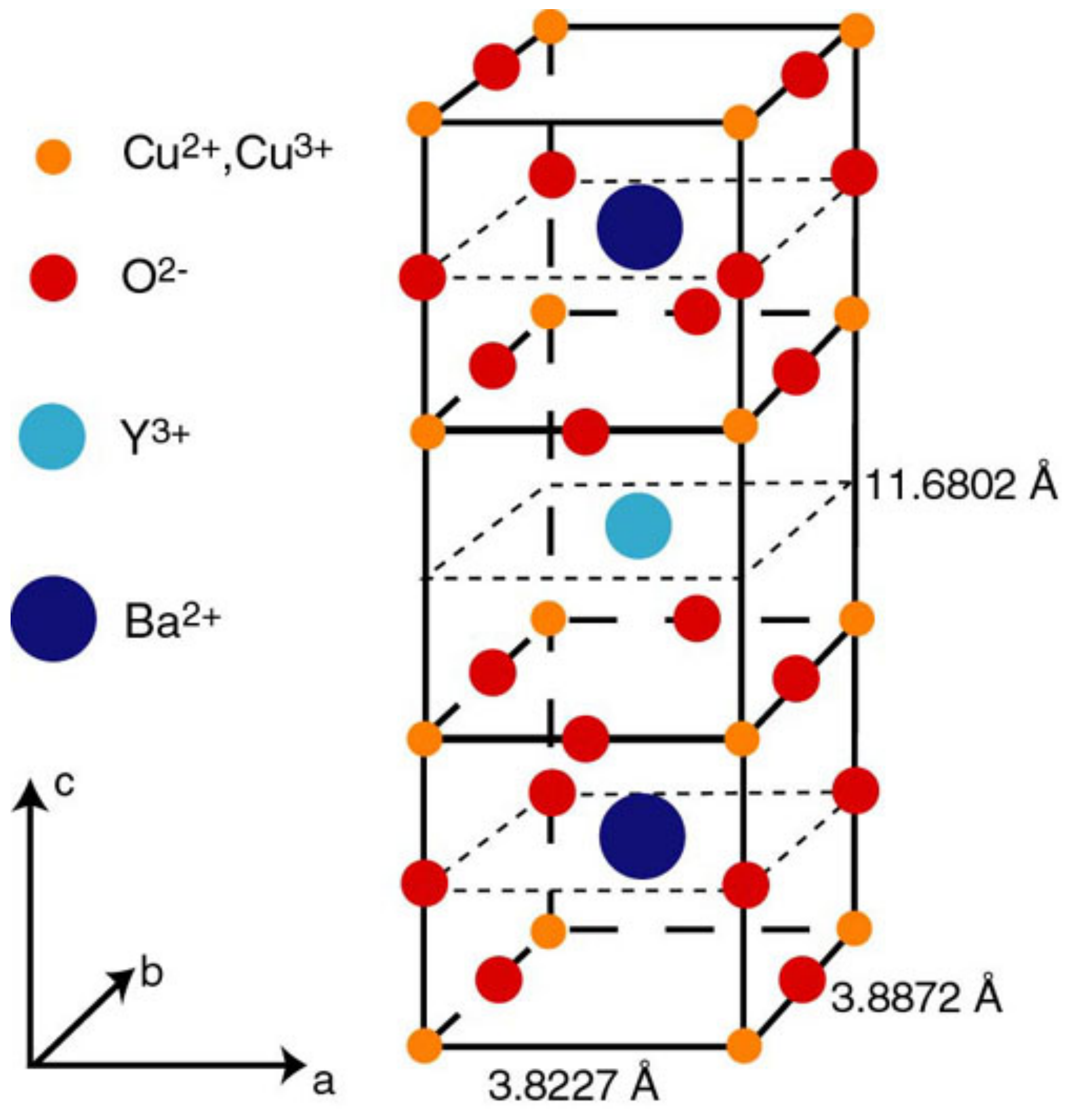
Aavishkar Patel
Flatiron

Haoyu Guo
Cornell

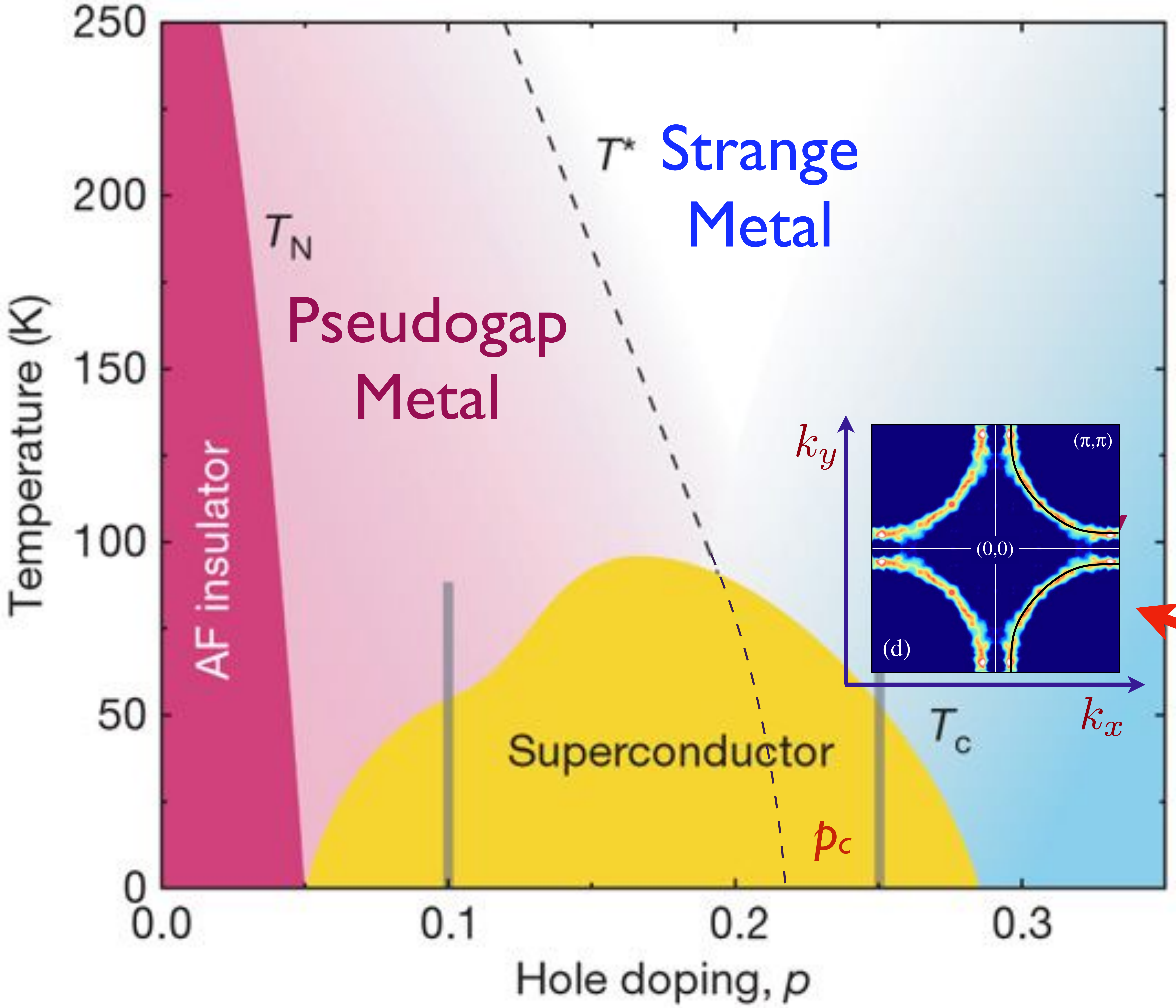


Ilya Esterlis
Wisconsin

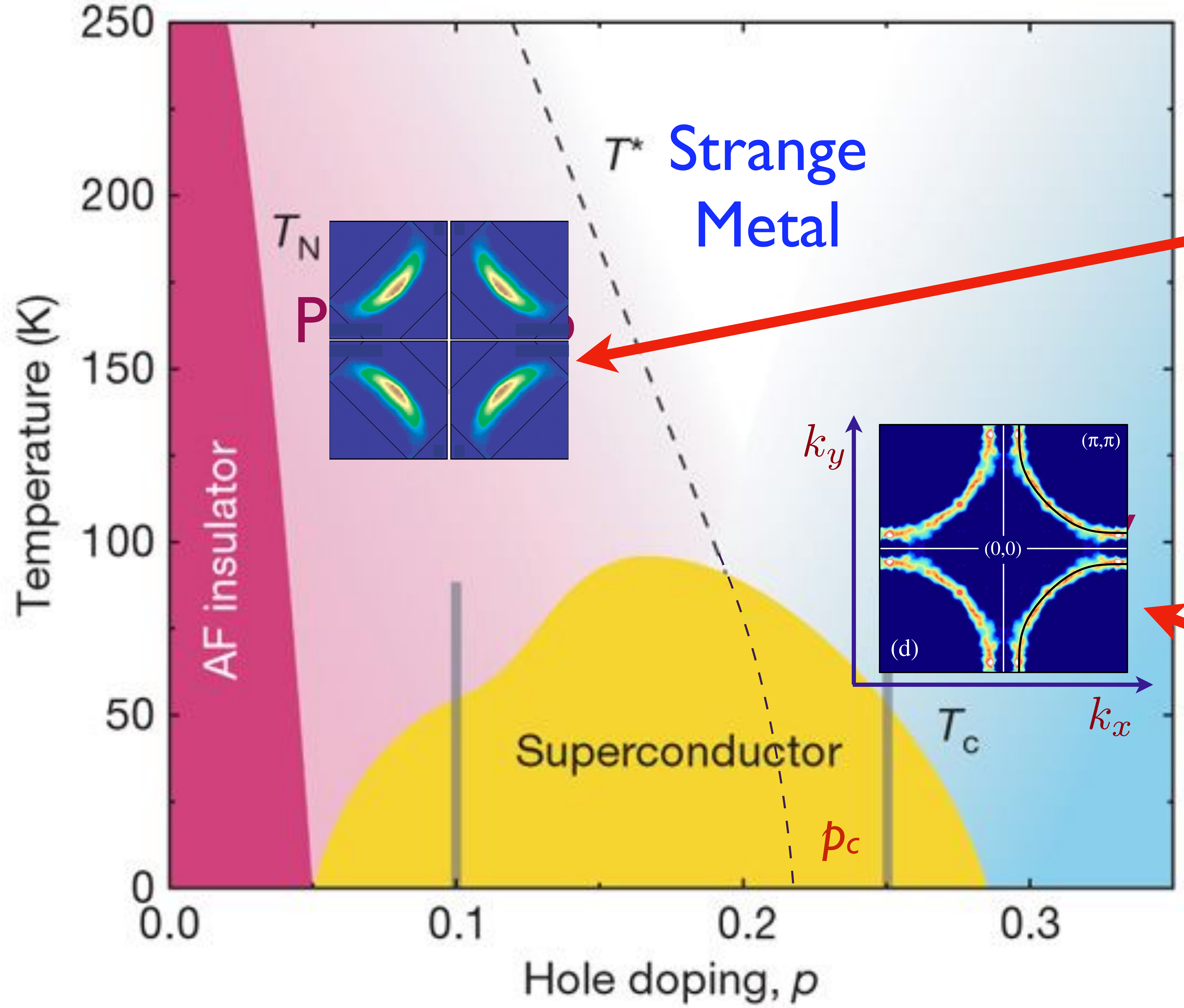

250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
Pseudogap
Metal
T*
Strange
Metal
Ordinary
Metal
Superconductor
T_c
p_c


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

$YBa_2Cu_3O_{6+x}$



Fermi surface separating occupied and empty electron momenta.
As expected,
in an ordinary metal



"Pseudogap metal"
Fermi surface
modified by
electron-electron
interactions

Fermi surface
separating occupied and
empty electron momenta.
As expected,
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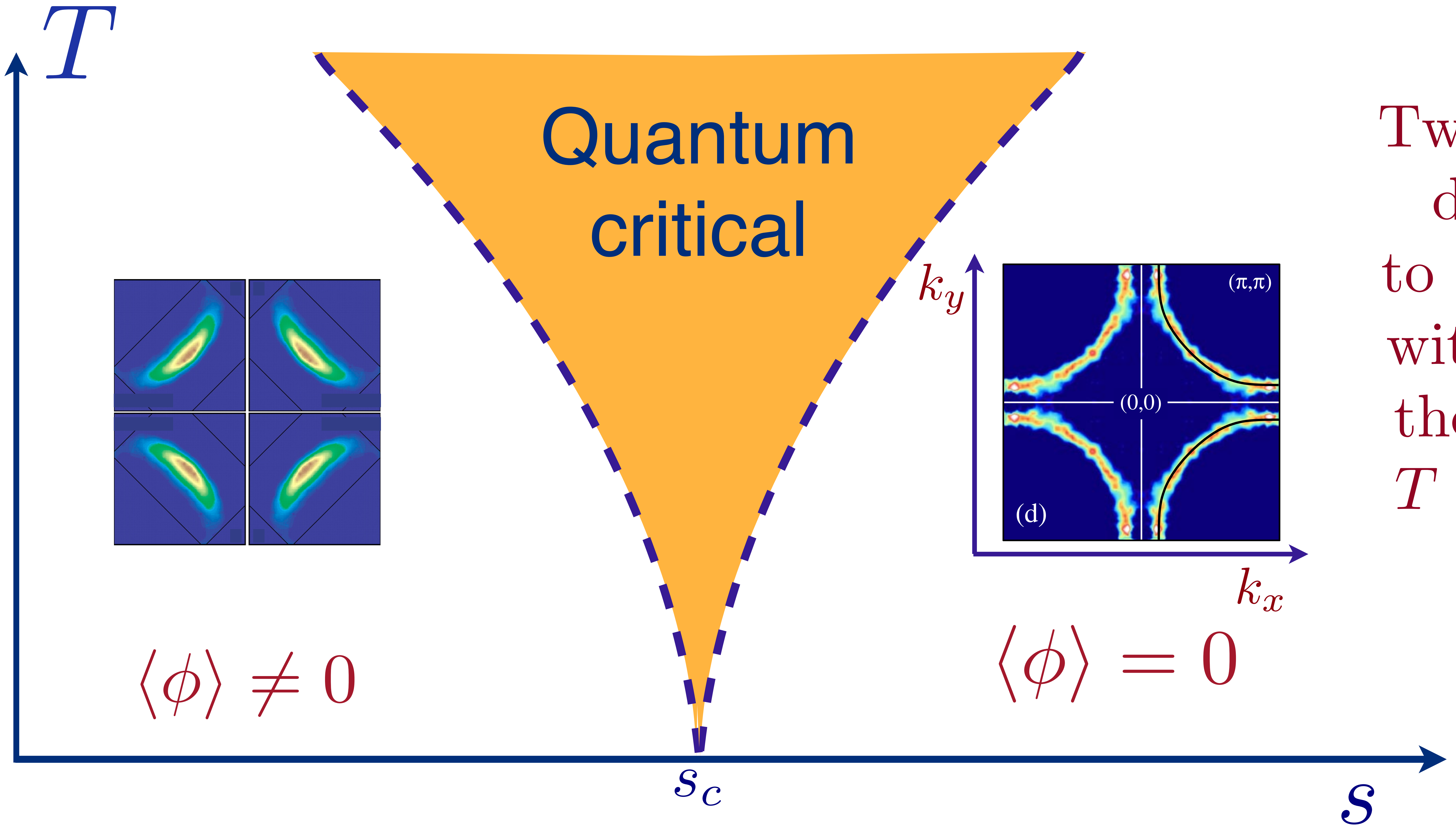
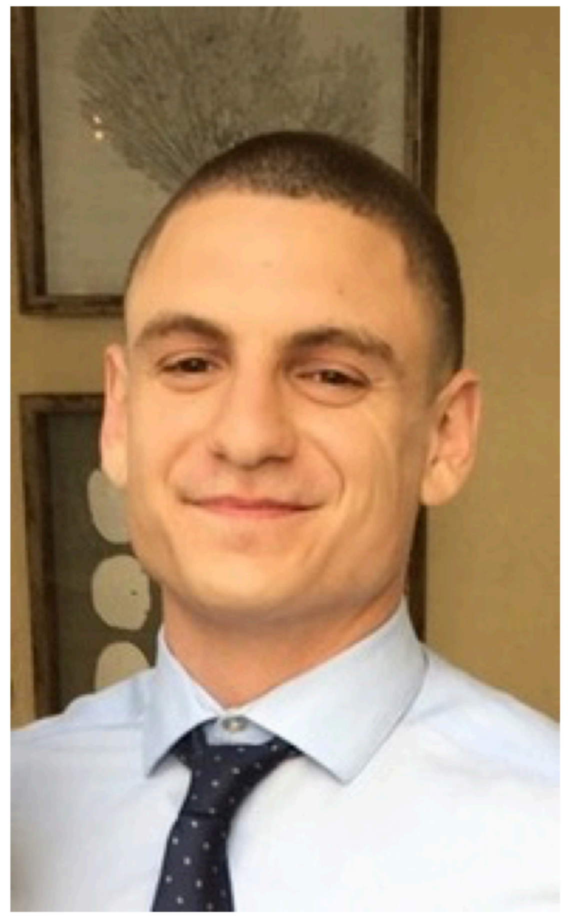
Quantum phase transition of Fermi surface change



Two-dimensional YSYK model describes electrons coupled to a boson ϕ driving the QPT, with spatial randomness in s_c, the position of the underlying $T = 0$ quantum critical point.

Strange metal and superconductor in the two-dimensional Yukawa-Sachdev-Ye-Kitaev model

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esterlis, PRL **133**, 186502 (2024)



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Wisconsin

Haoyu Guo
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Davide Valentinis
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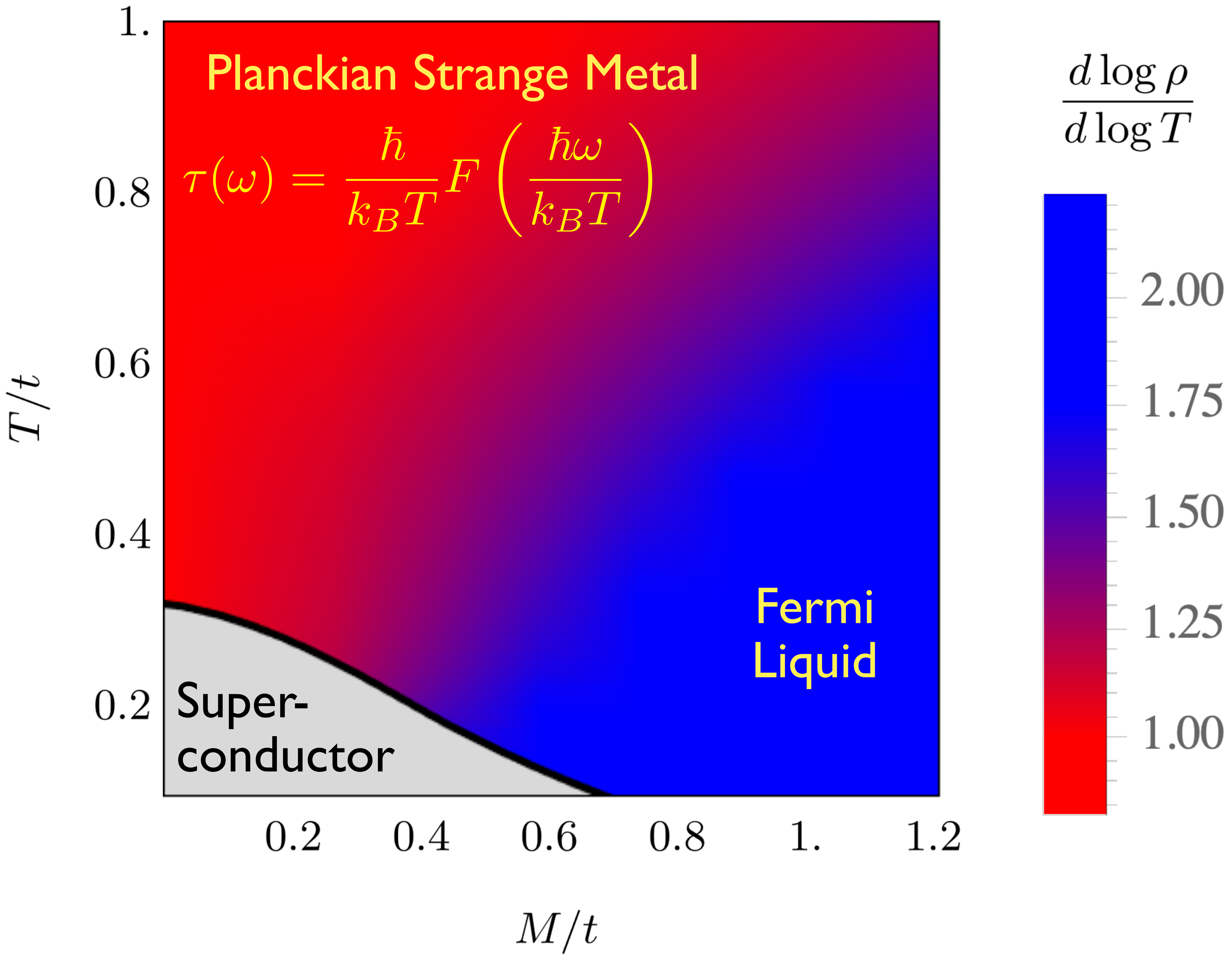
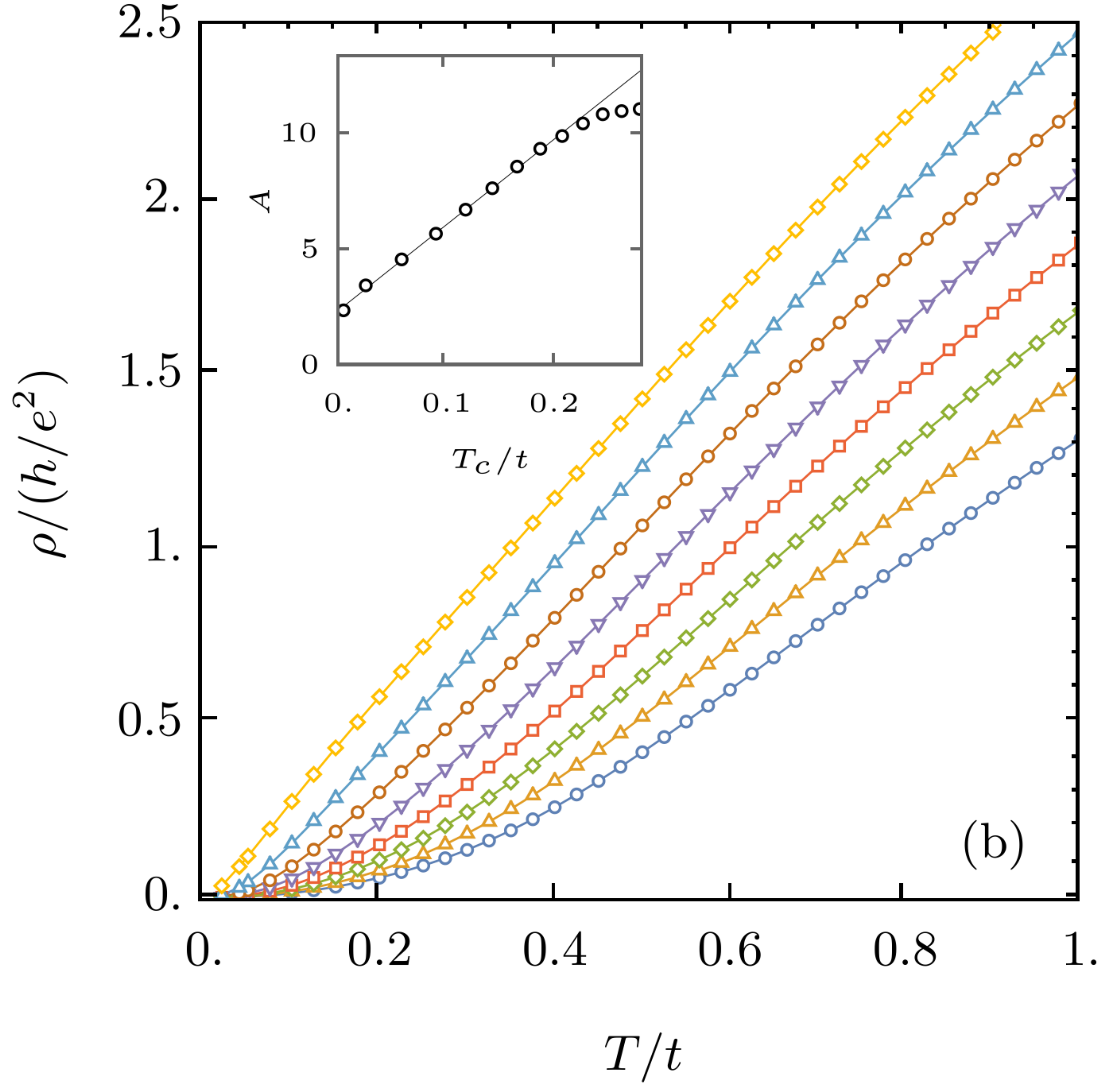


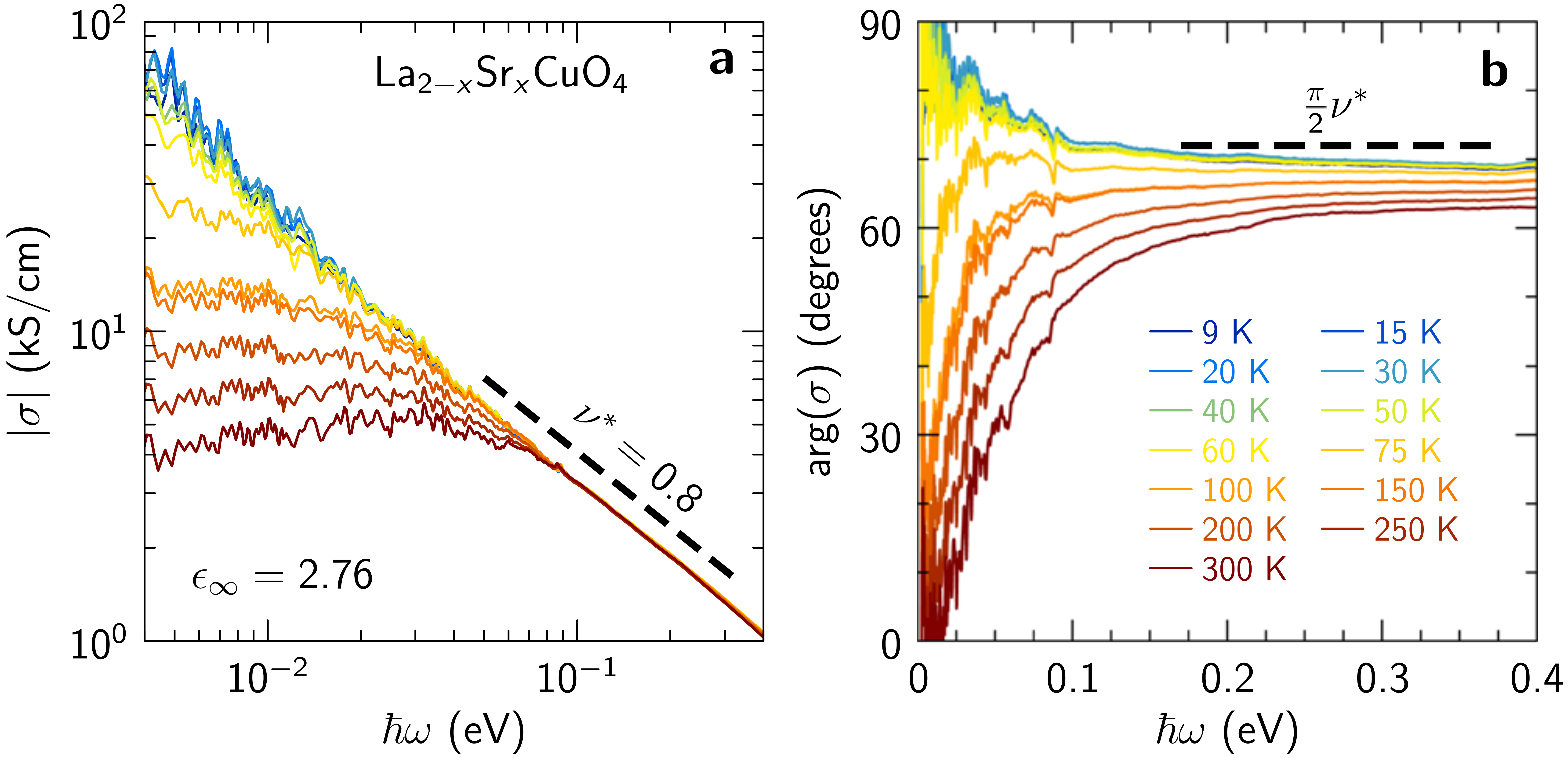


Reconciling scaling of the optical conductivity of cuprate superconductors with Planckian resistivity and specific heat

B. Michon, C. Berthod, C. W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges

Nature Communications **14**, Article number: 3033 (2023)

$$\sigma(\omega) = i\frac{e^2K/(\hbar d_c)}{\hbar\omega\dfrac{m^*(\omega)}{m} + i\dfrac{\hbar}{\tau(\omega)}}$$



La$_{2-x}$Sr$_x$CuO$_4$
$p = 0.24$
$T_c = 19$ K

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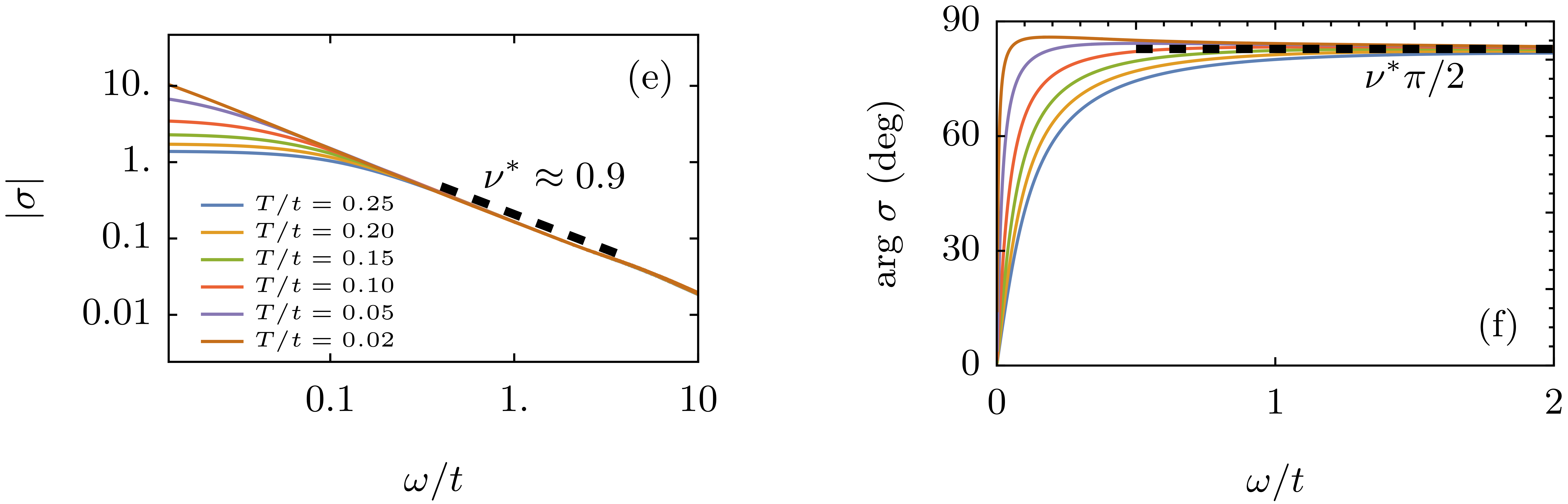

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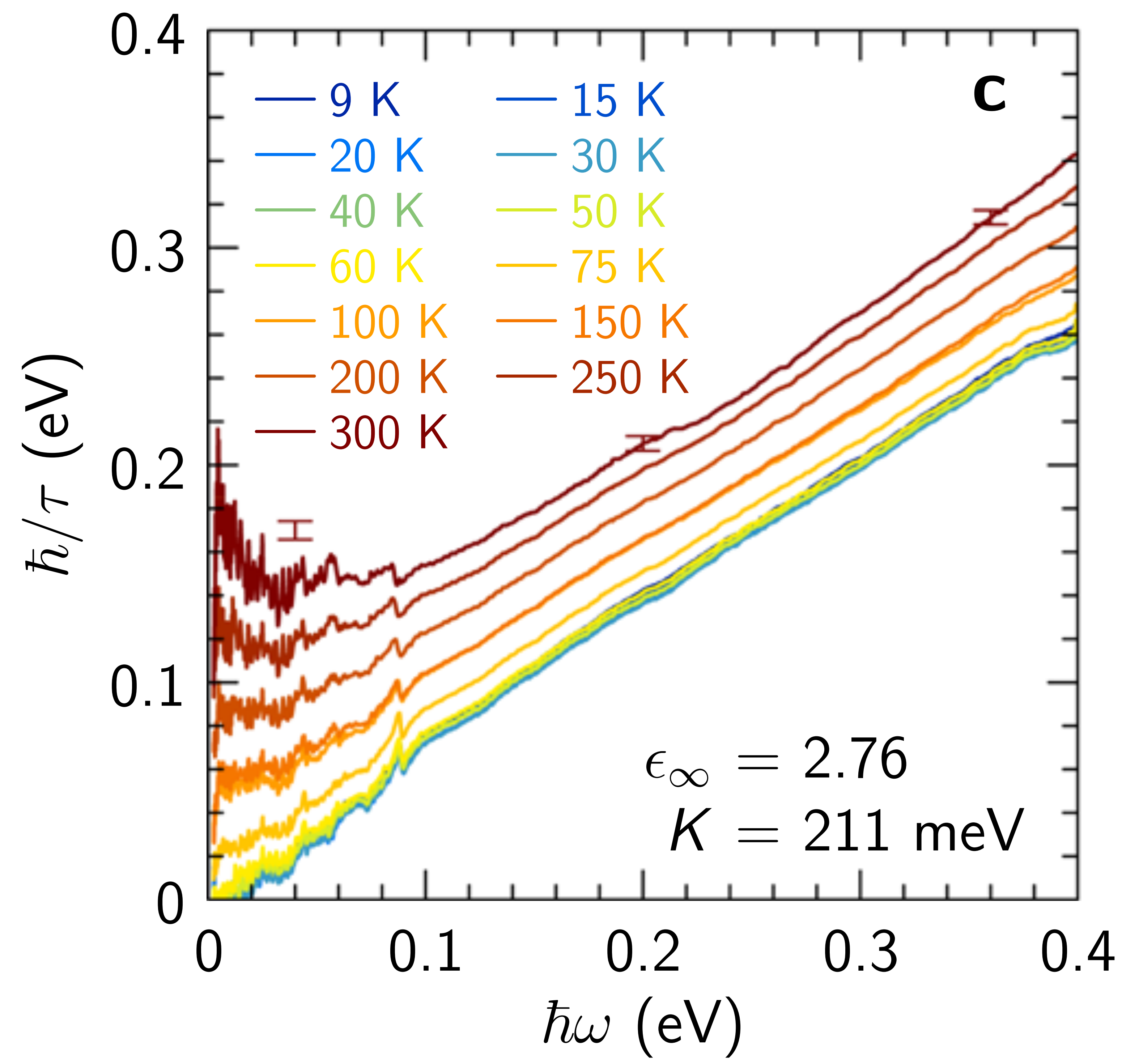

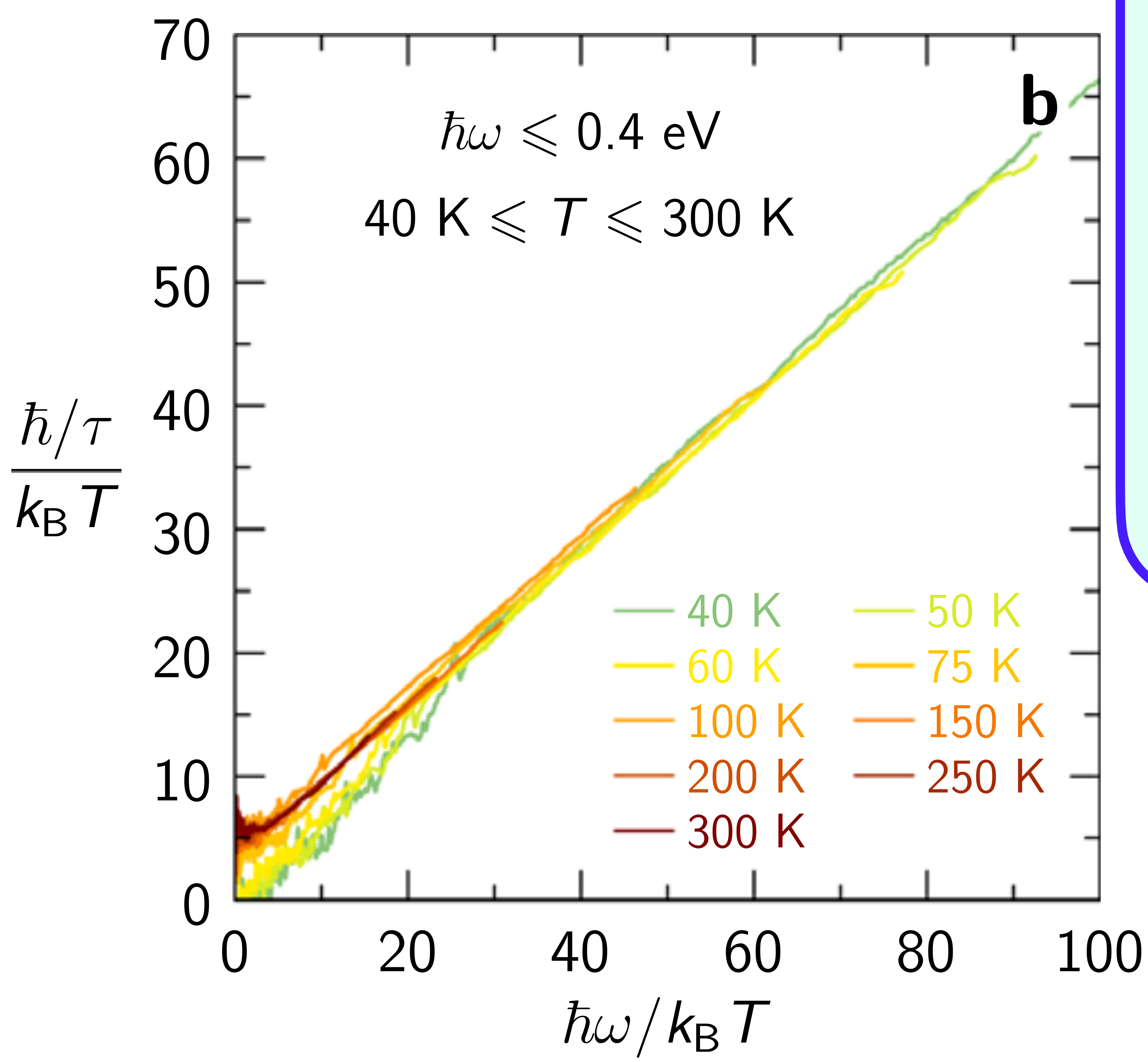

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and entropy
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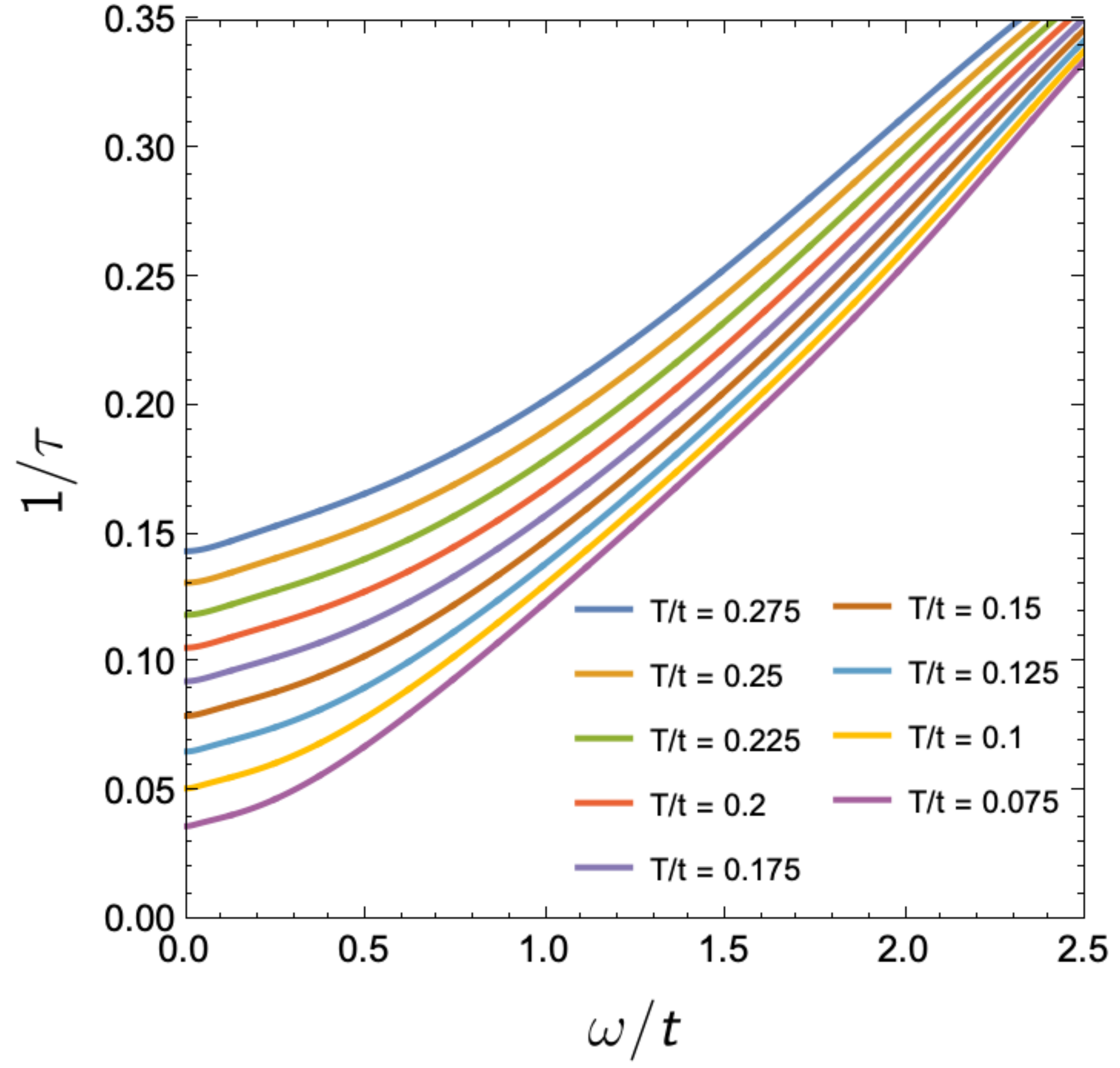

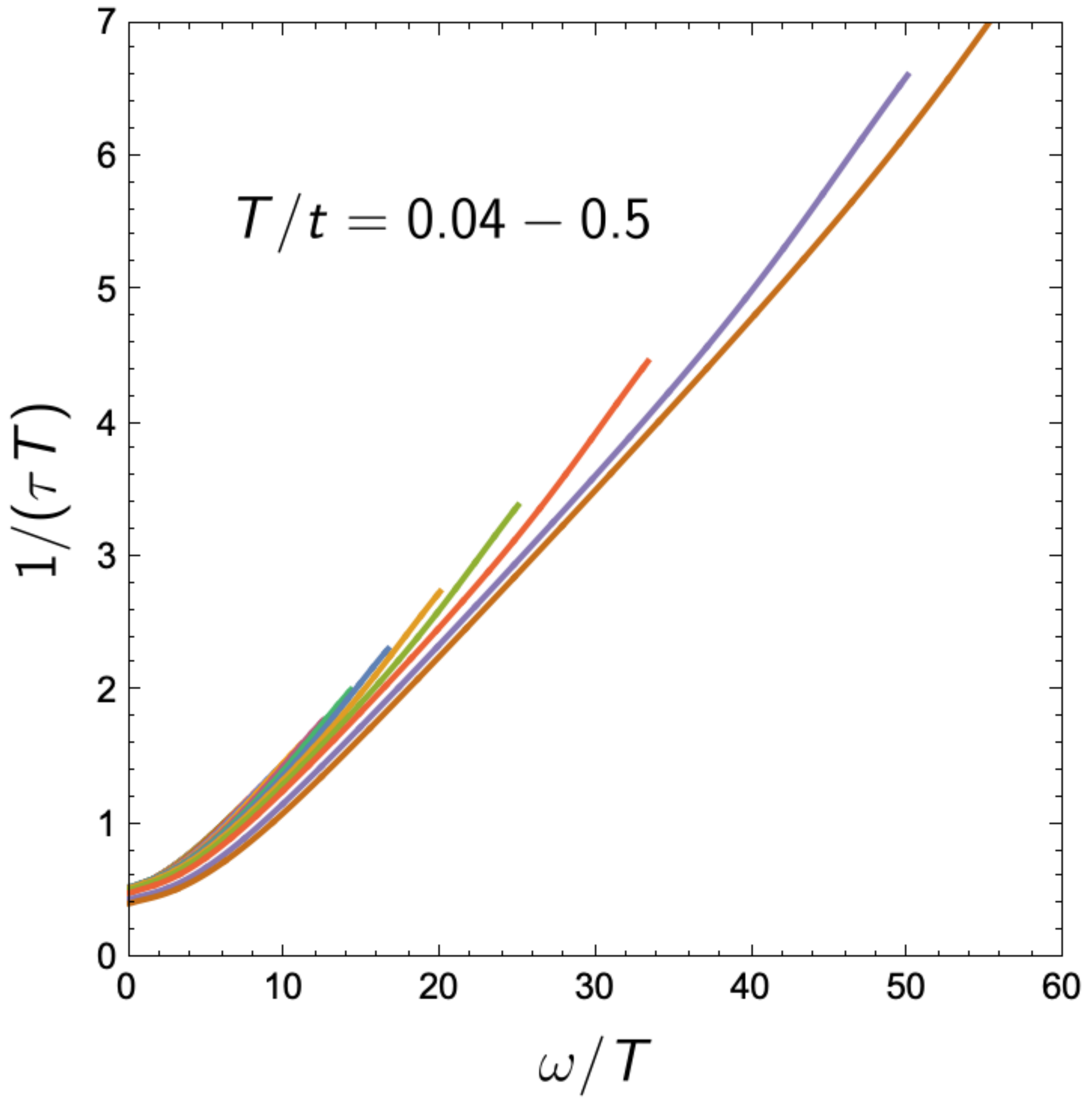

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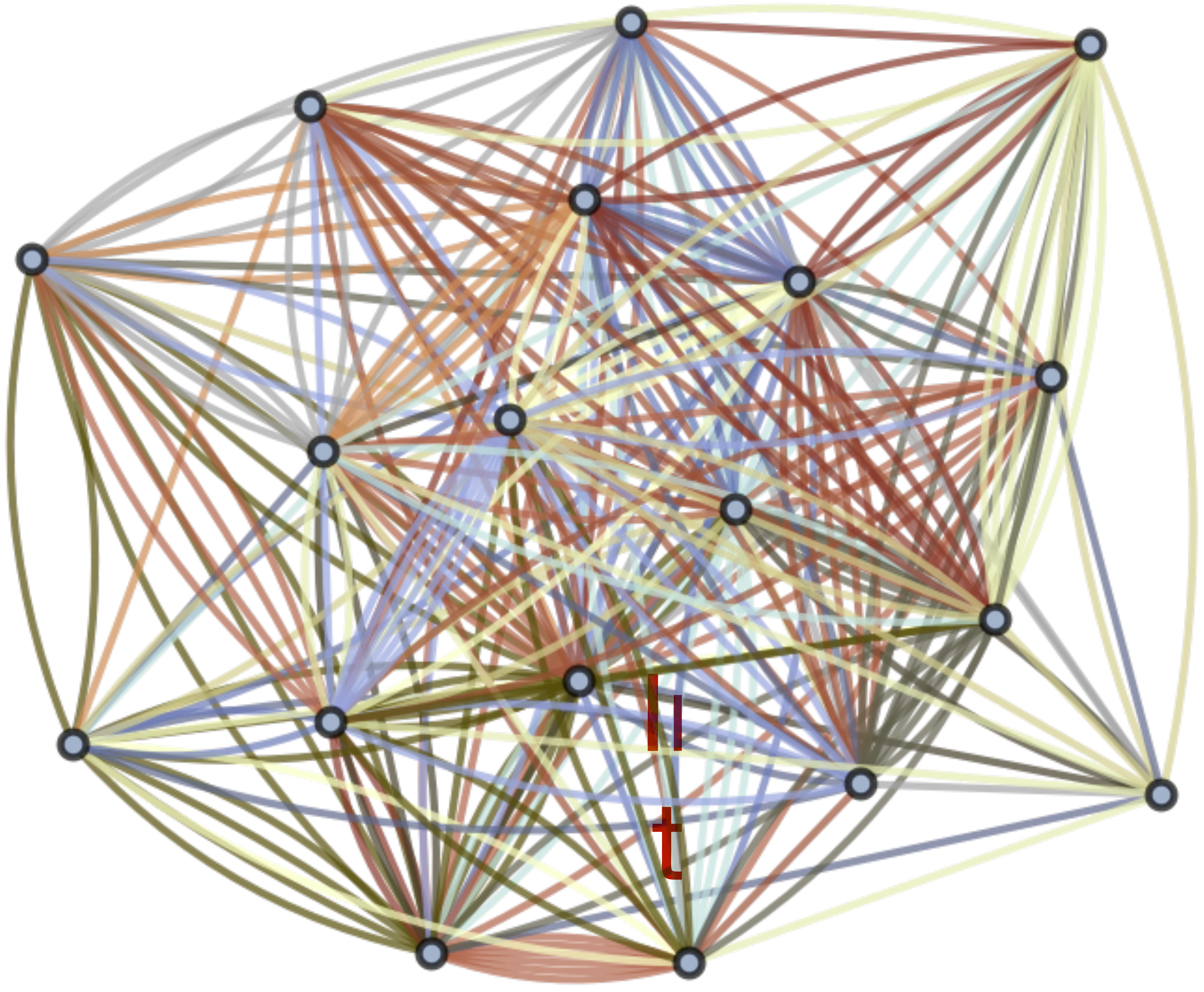
and entropy
$S(T \to 0) \sim T \ln(1/T)$
in 2d-YSYK model
(unlike zero temperature entropy in SYK model).

Recap

The Sachdev-Ye-Kitaev (SYK) model

The SYK model describes multi-particle quantum entanglement resulting in the loss of identity of the particles



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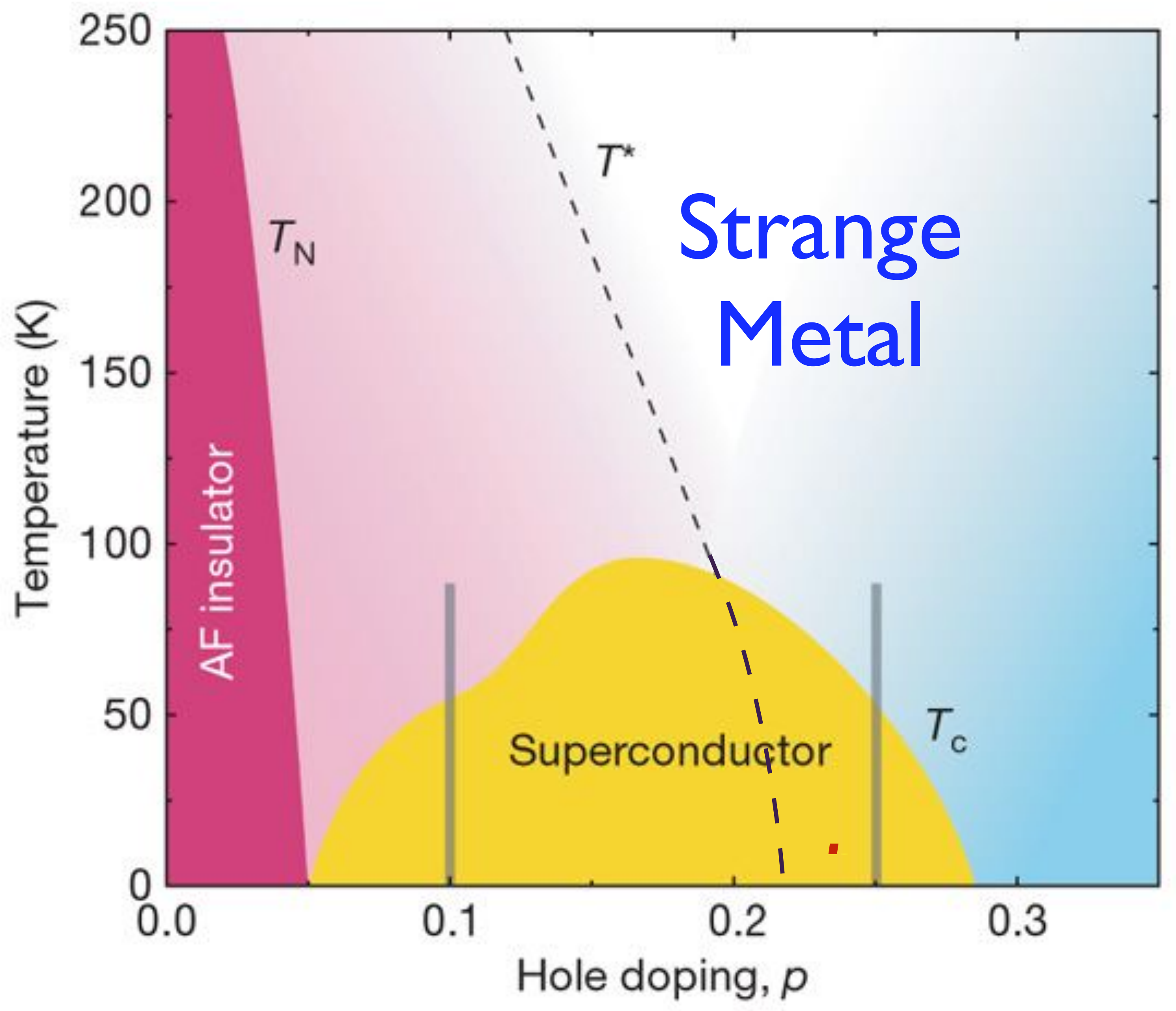
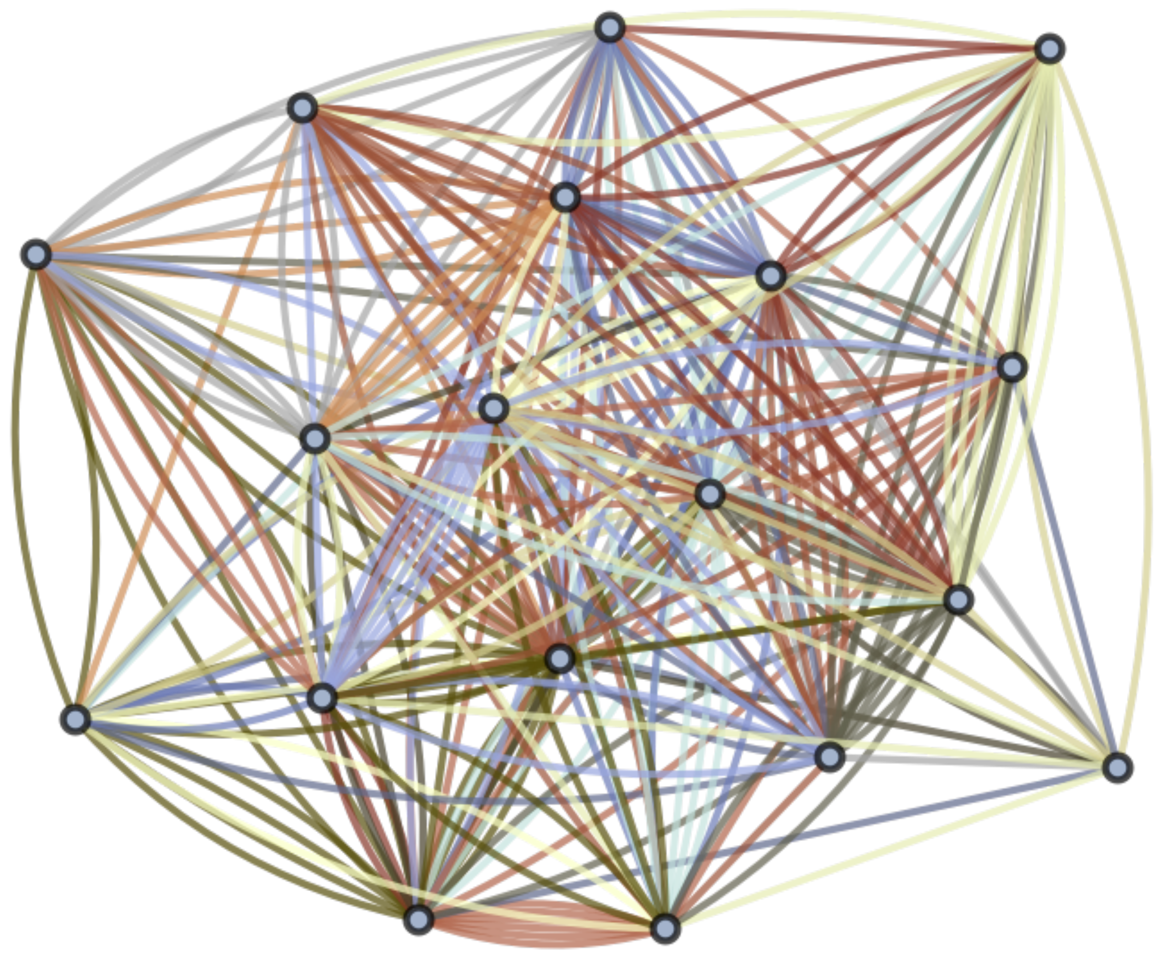


A 2d-YSYK theory describes the **strange metal** behavior of numerous quantum materials



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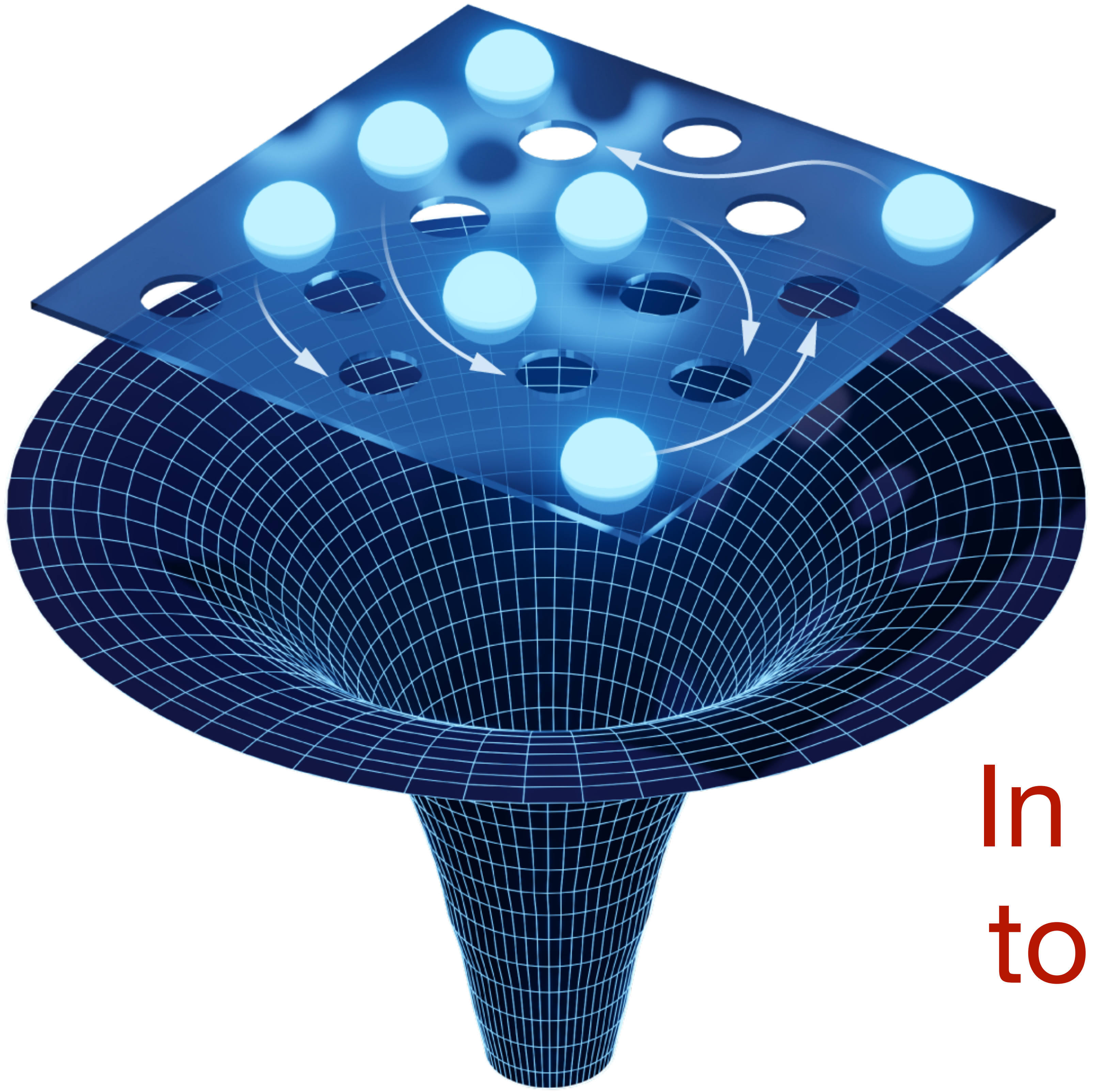

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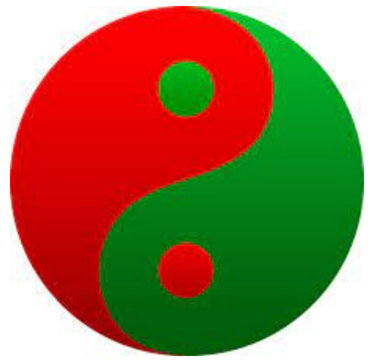

In a *dual* set of variables the SYK model has led to the computation of the low energy density of states of ***charged black holes***