

Quantum entanglement in nature: superconductors, quantum field theory, black holes

Harvard University
January 20, 2026

Subir Sachdev



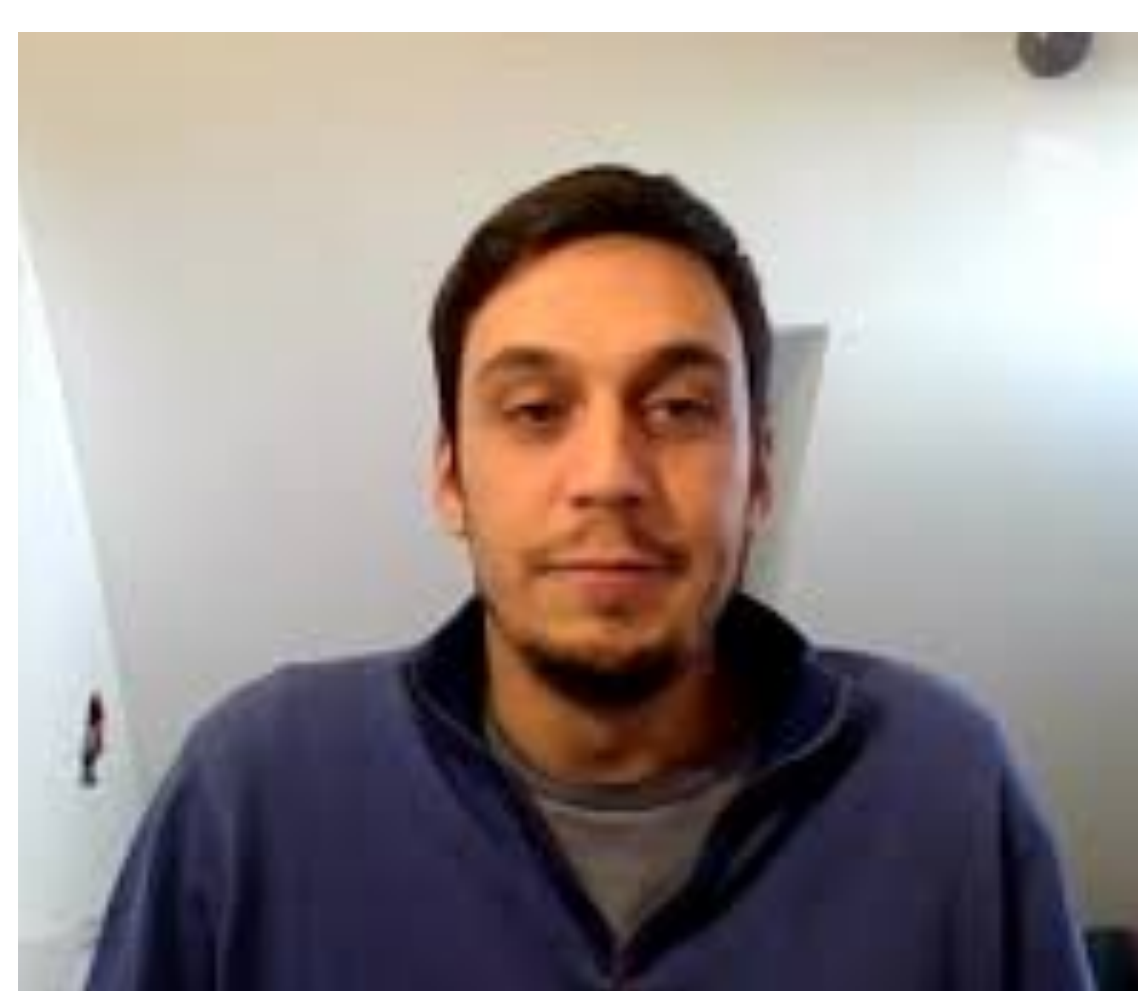
PHYSICS



HARVARD



Maine Christos
Caltech



Pietro Bonetti



Alexander
Nikolaenko



Aavishkar Patel
ICTS, Bengaluru

arXiv > cond-mat > arXiv:2508.20164

Condensed Matter > Strongly Correlated Electrons

[Submitted on 27 Aug 2025 (v1), last revised 28 Dec 2025 (this version, v6)]

Fractionalized Fermi liquids and the cuprate phase diagram

arXiv > cond-mat > arXiv:2512.23962

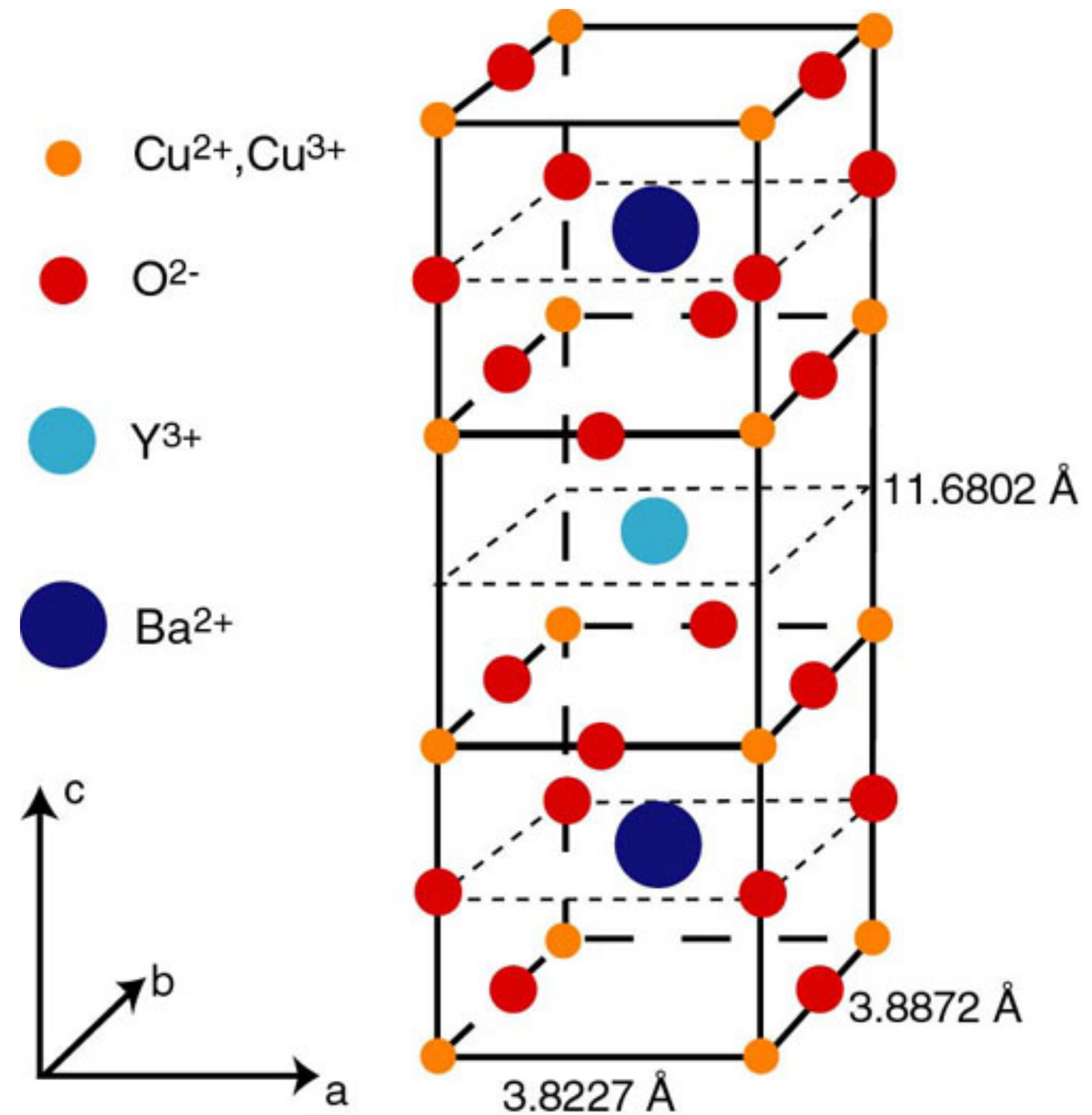
Condensed Matter > Strongly Correlated Electrons

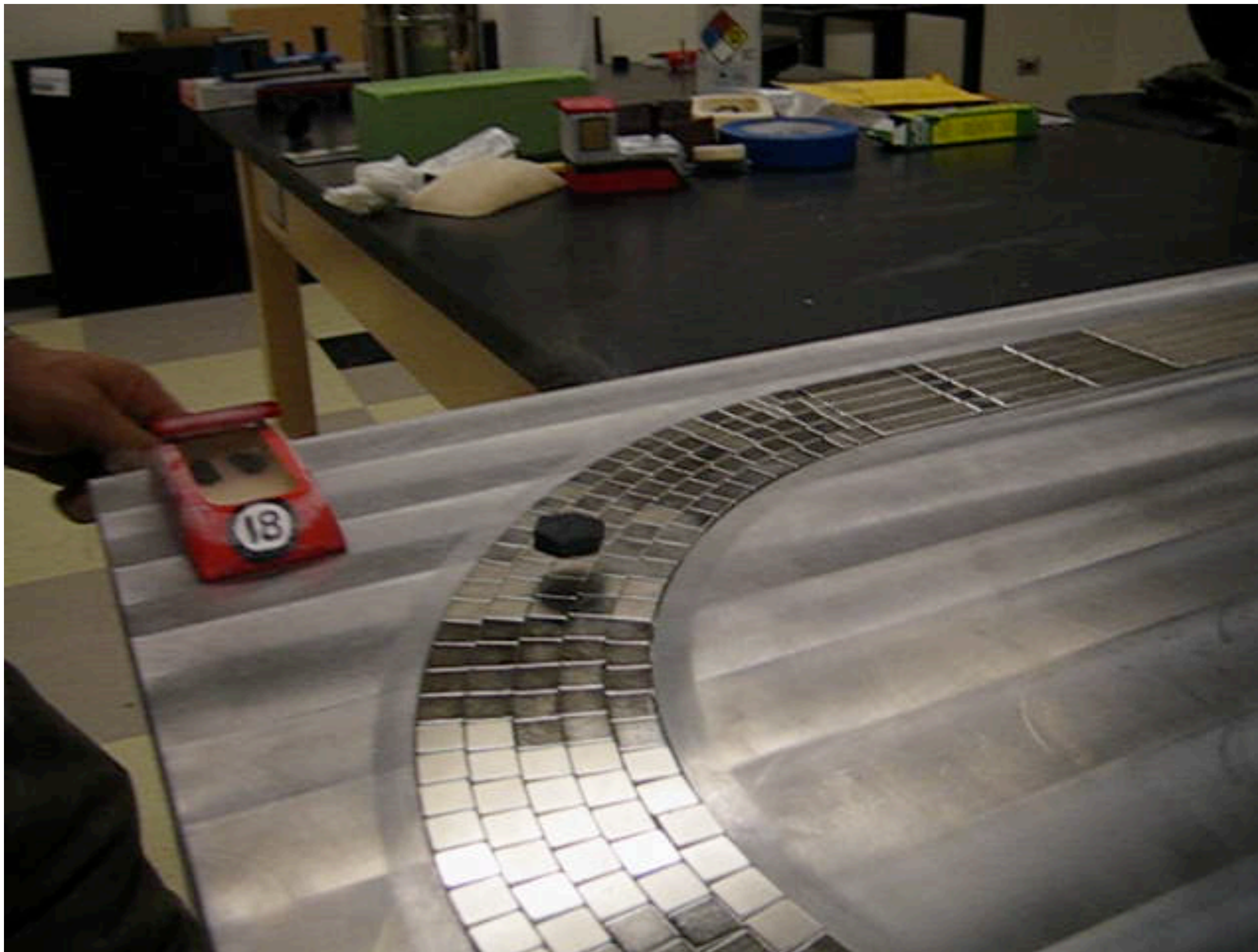
[Submitted on 30 Dec 2025 (v1), last revised 13 Jan 2026 (this version, v3)]

Lectures on insulating and conducting quantum spin liquids

Superconductors

Cuprate high temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

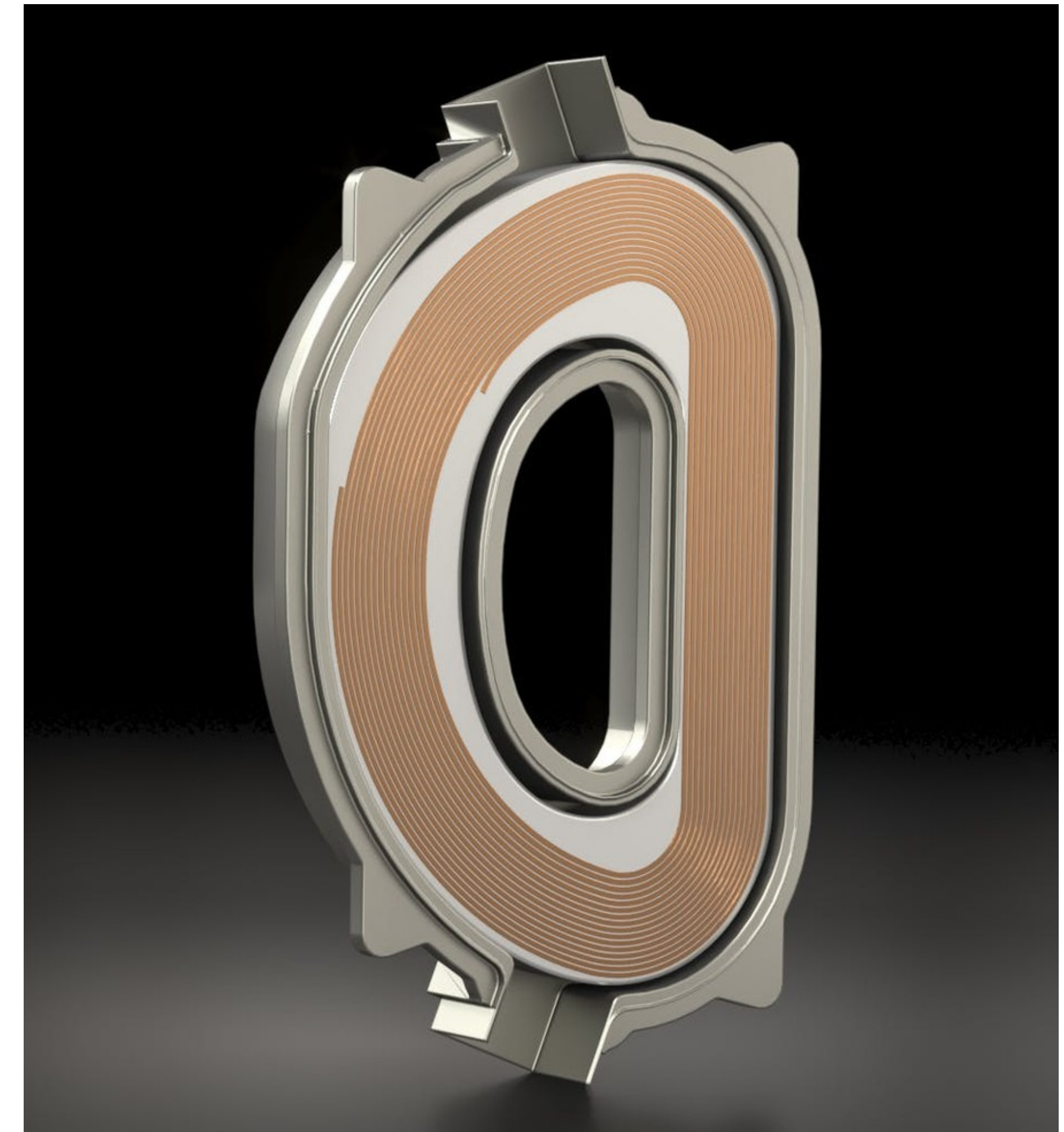
HTS Magnets: Enabling Technology

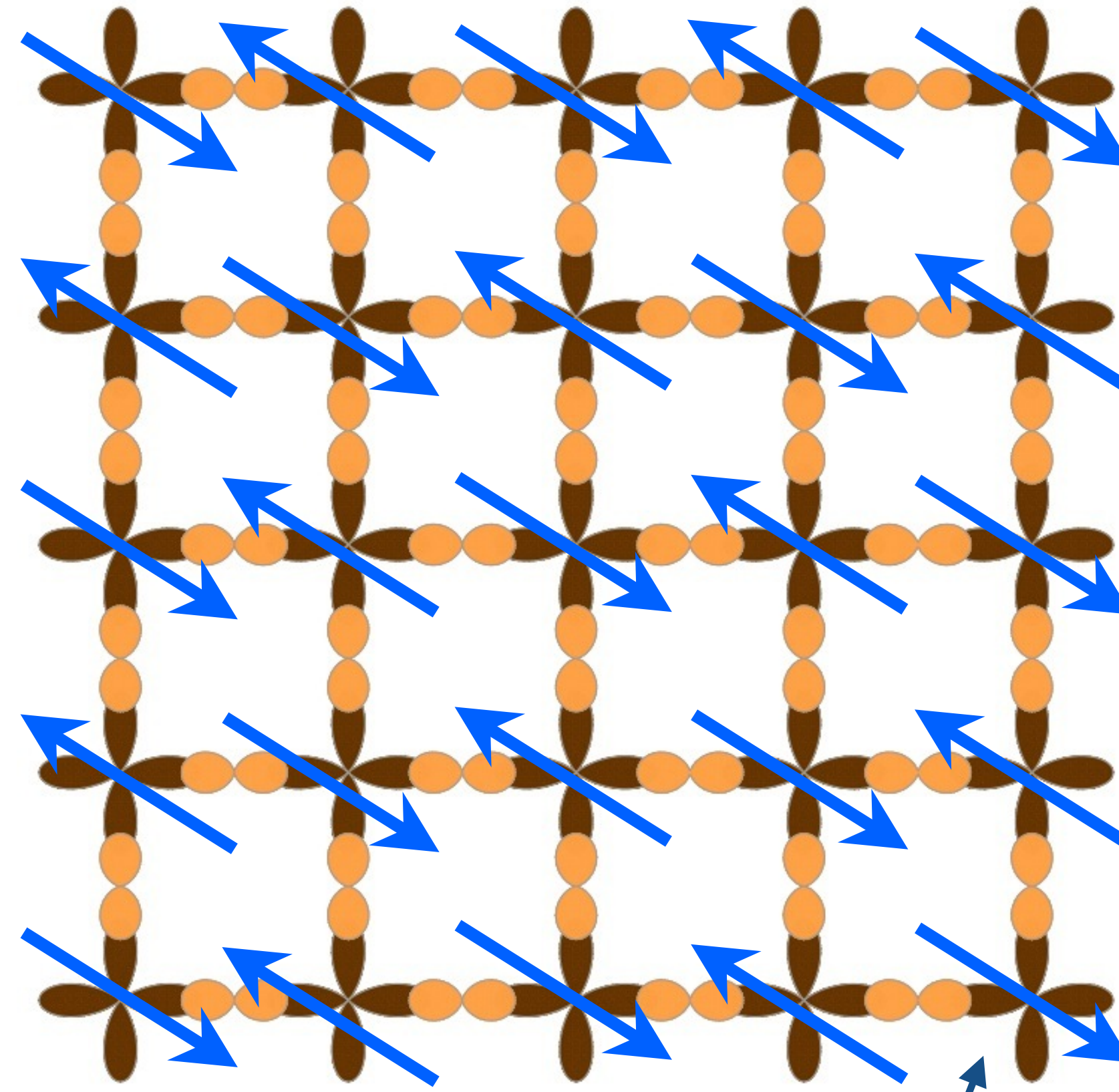
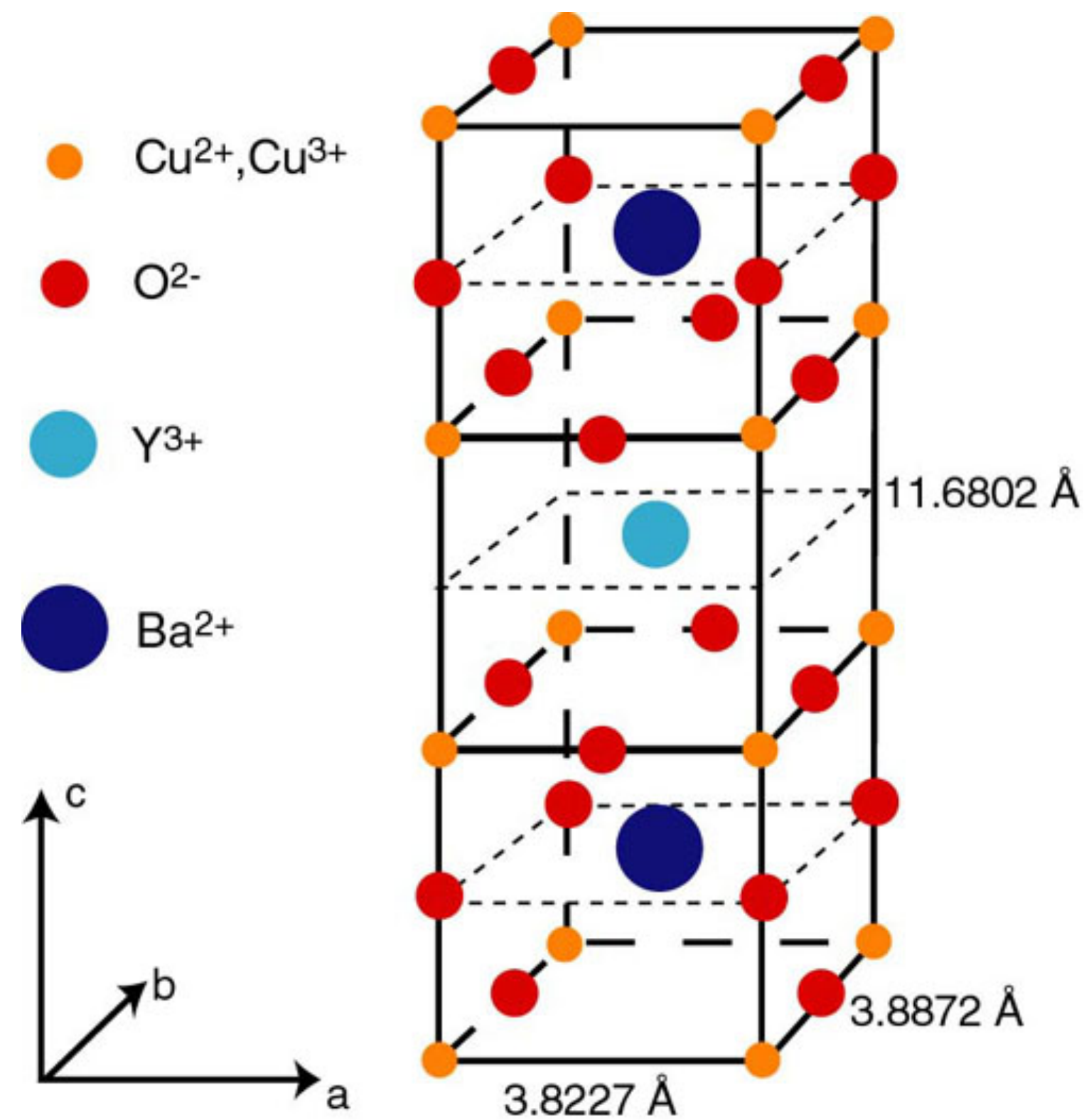
The surest path to limitless,
clean, fusion energy

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

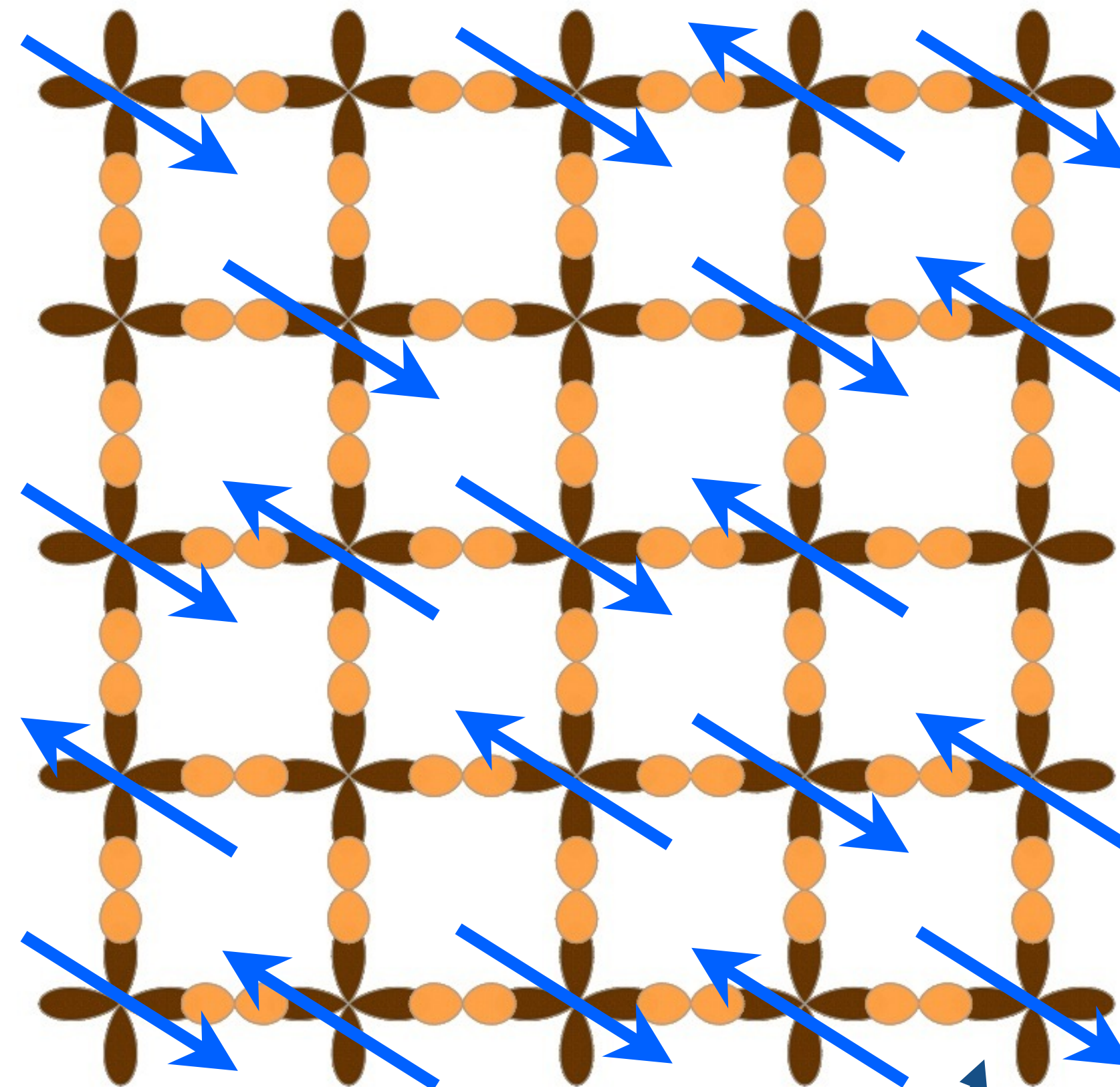
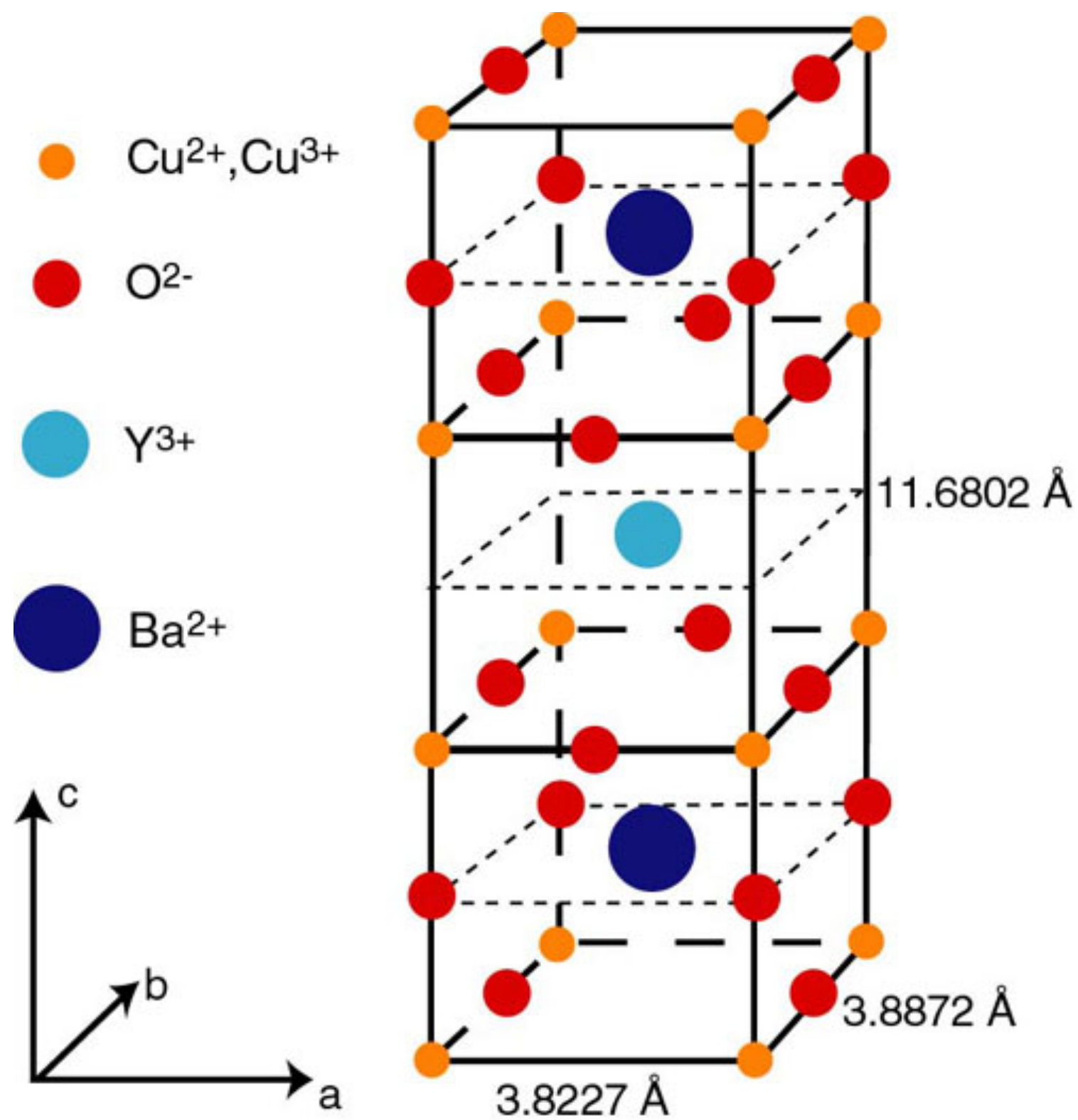


Commonwealth
Fusion Systems



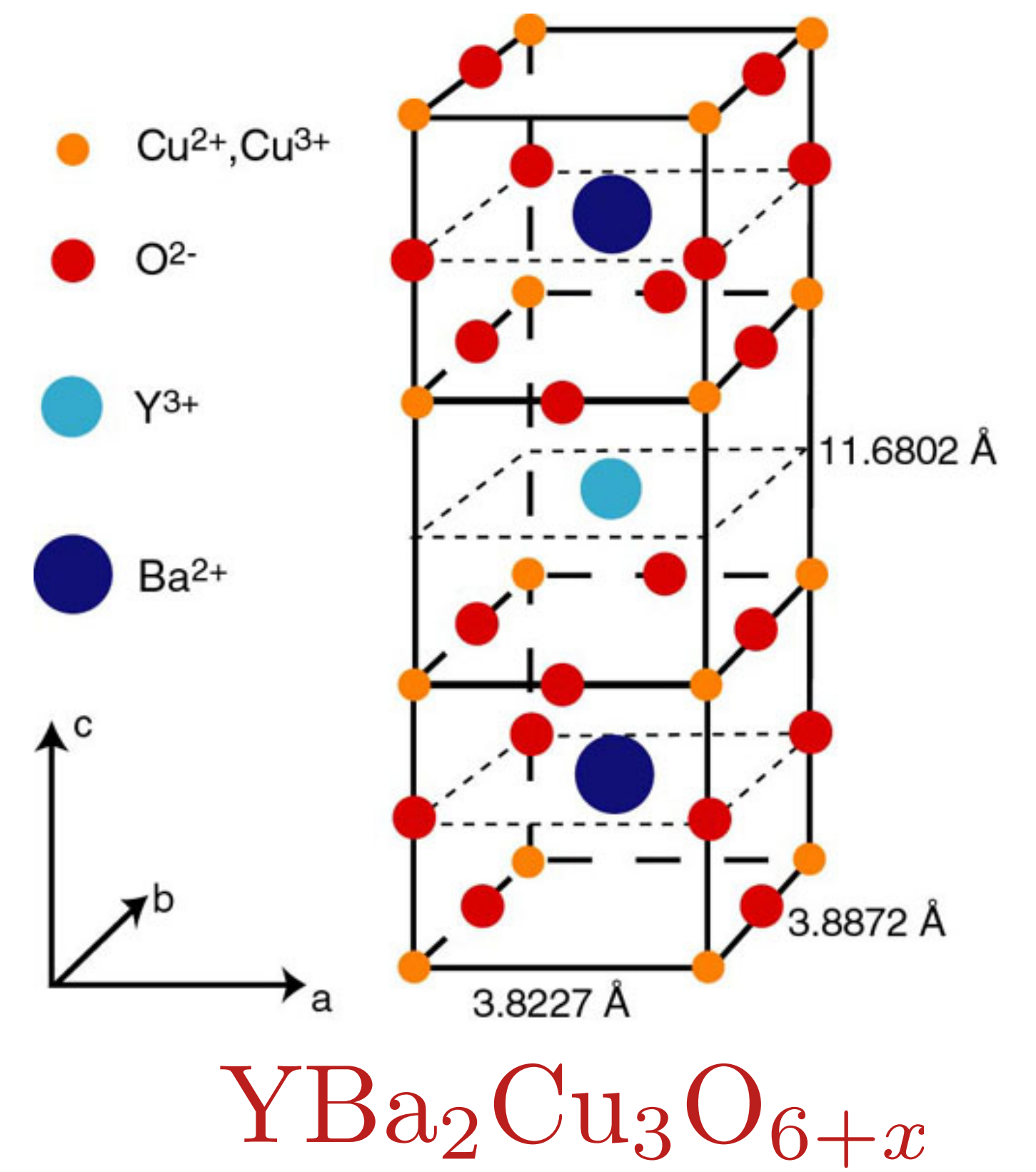
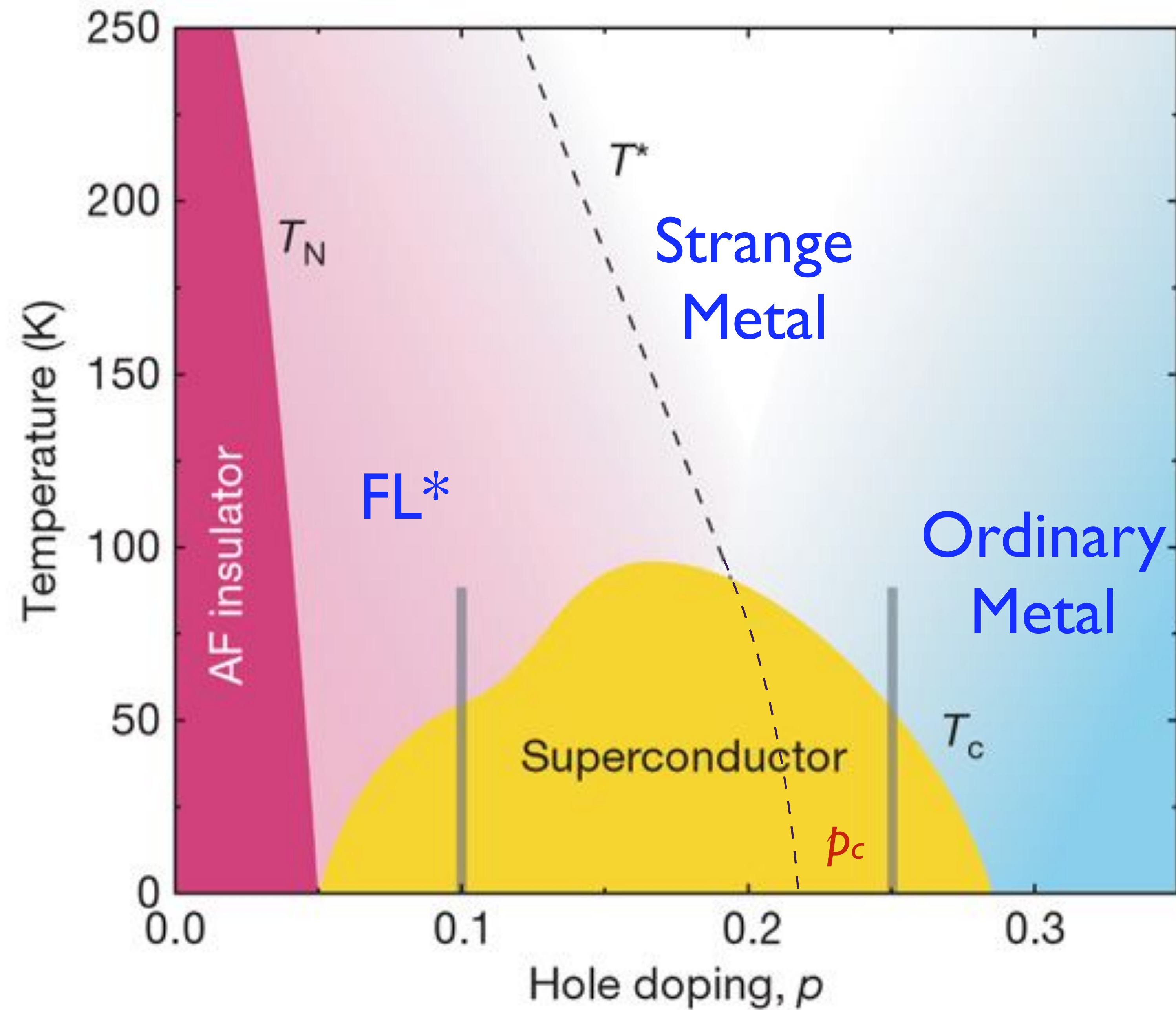


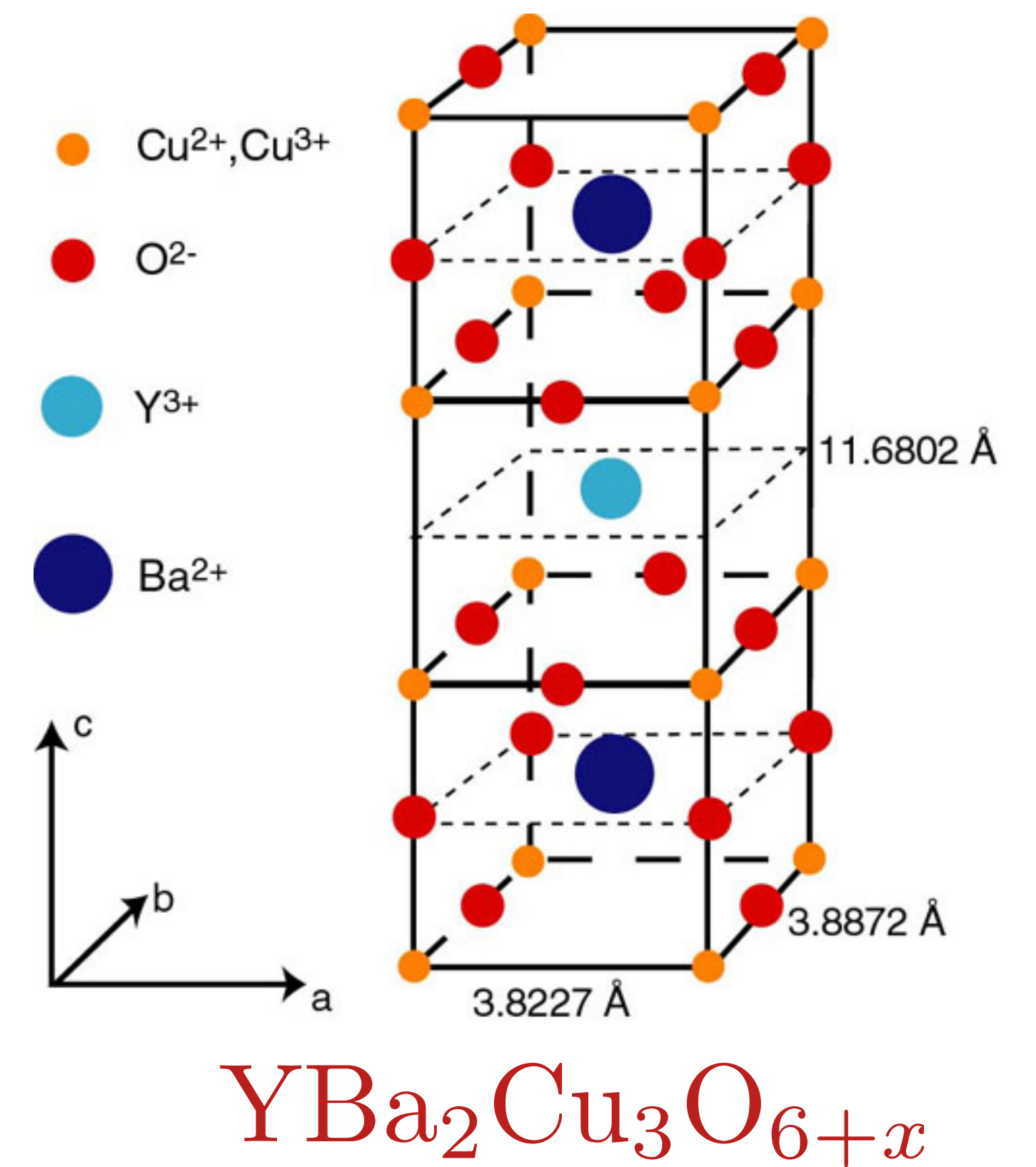
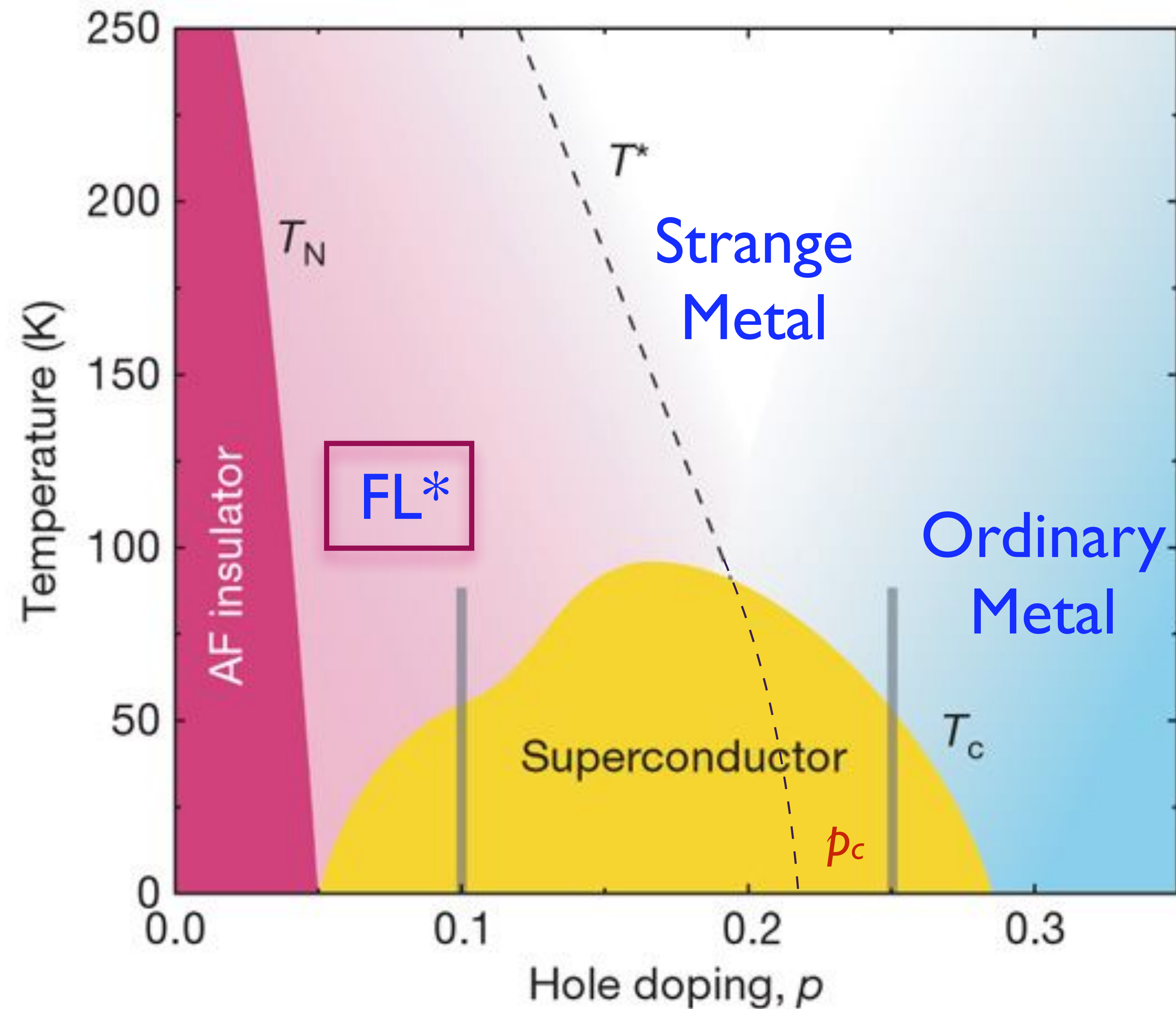
Insulating antiferromagnet with one electron per site



Cu

High temperature superconductor obtained upon doping the antiferromagnet with density p holes.

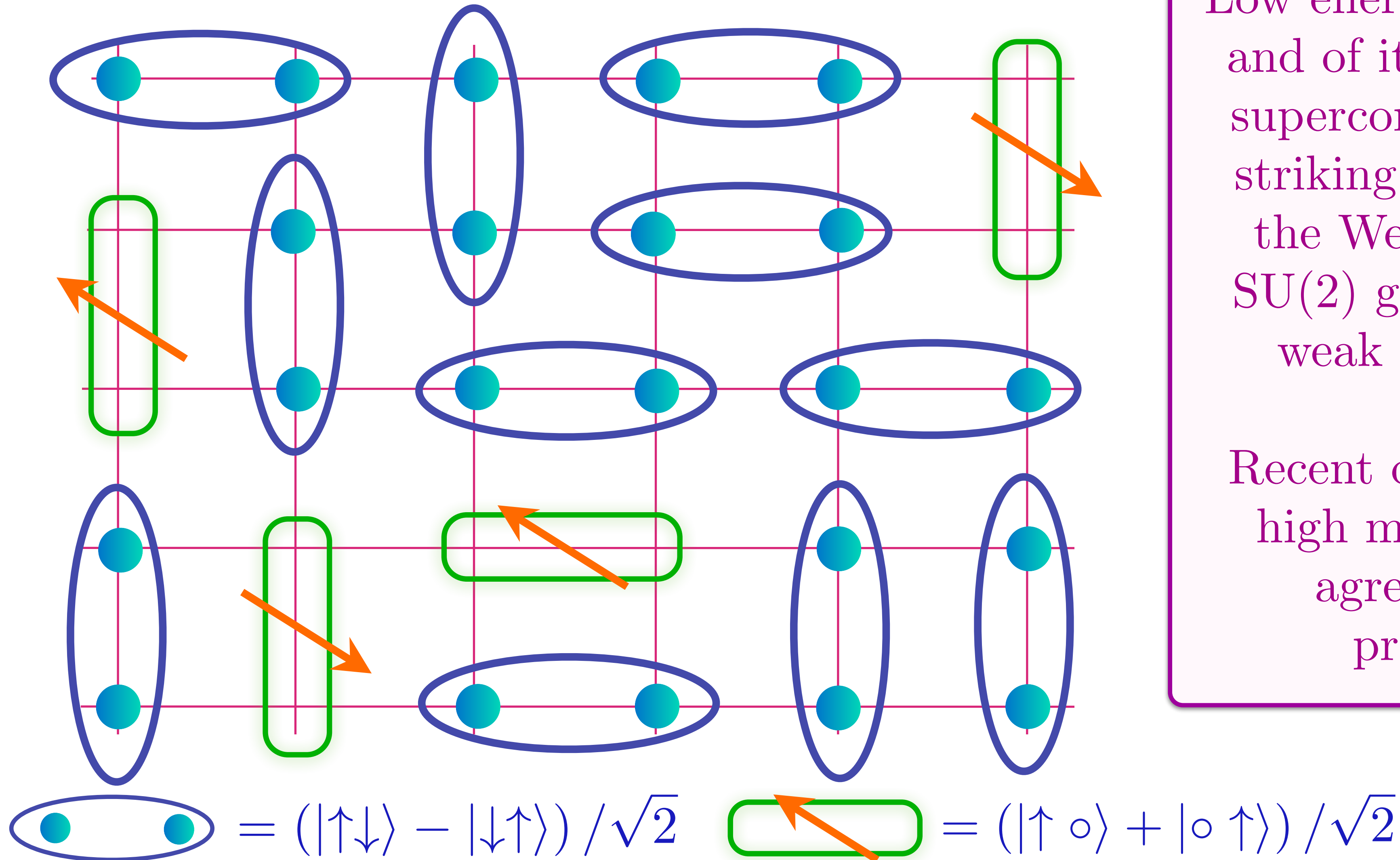




**Fractionalized
Fermi
Liquid**

Doping an insulating antiferromagnet with holes of density p

FL*

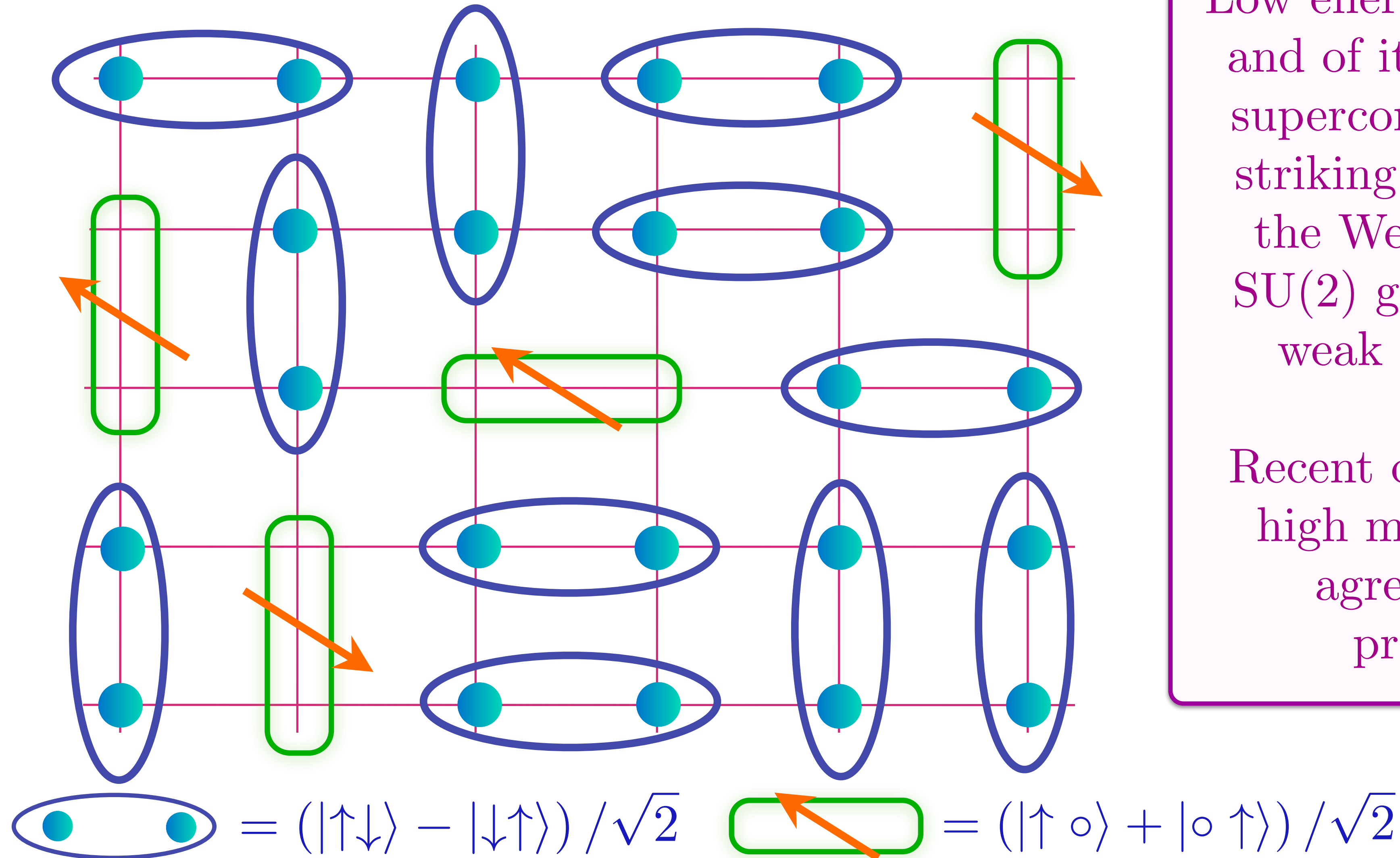


Low energy of this state, and of its transition to superconductivity, has striking similarities to the Weinberg-Salam SU(2) gauge theory of weak interactions.

Recent observations in high magnetic fields agree with our predictions

Doping an insulating antiferromagnet with holes of density p

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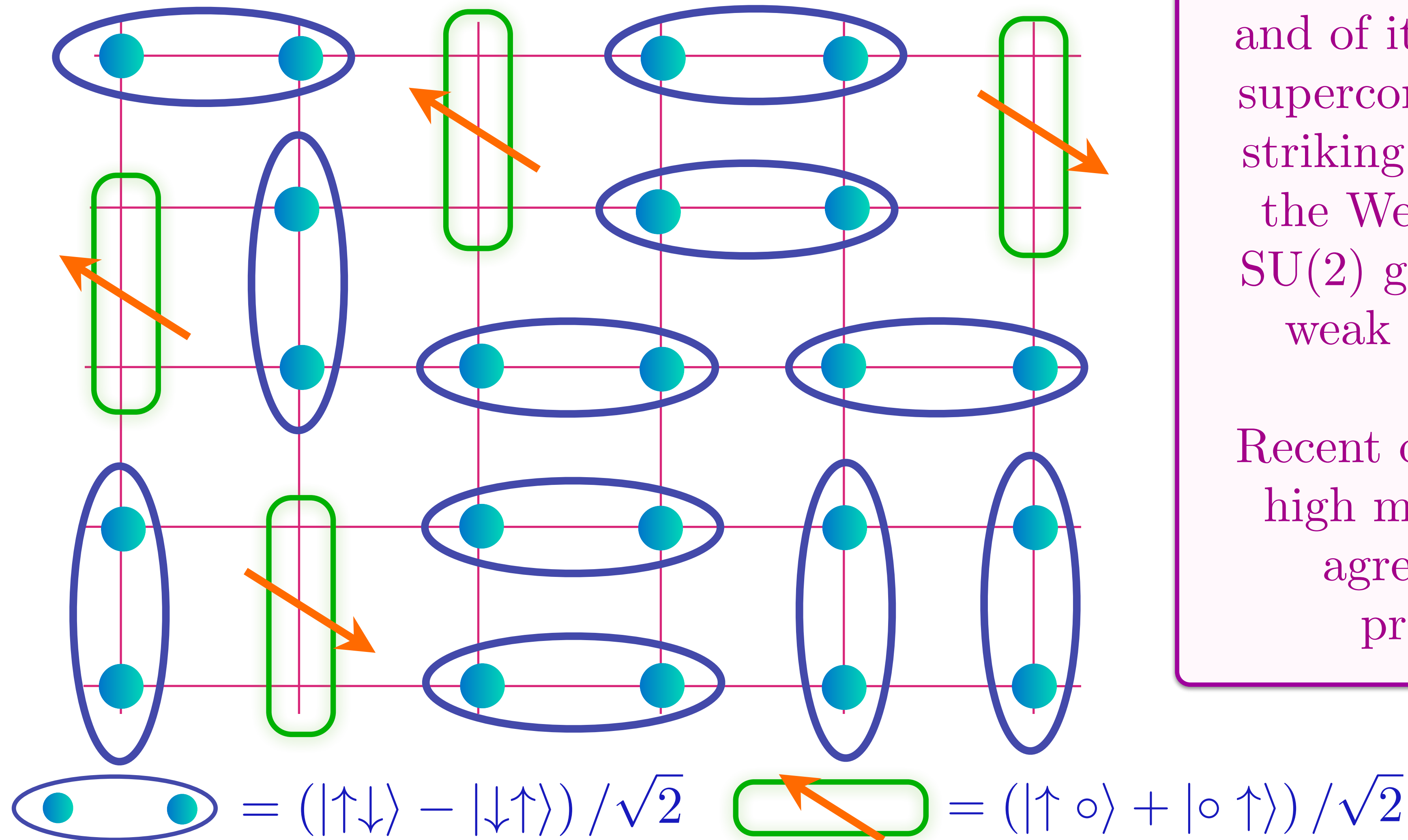


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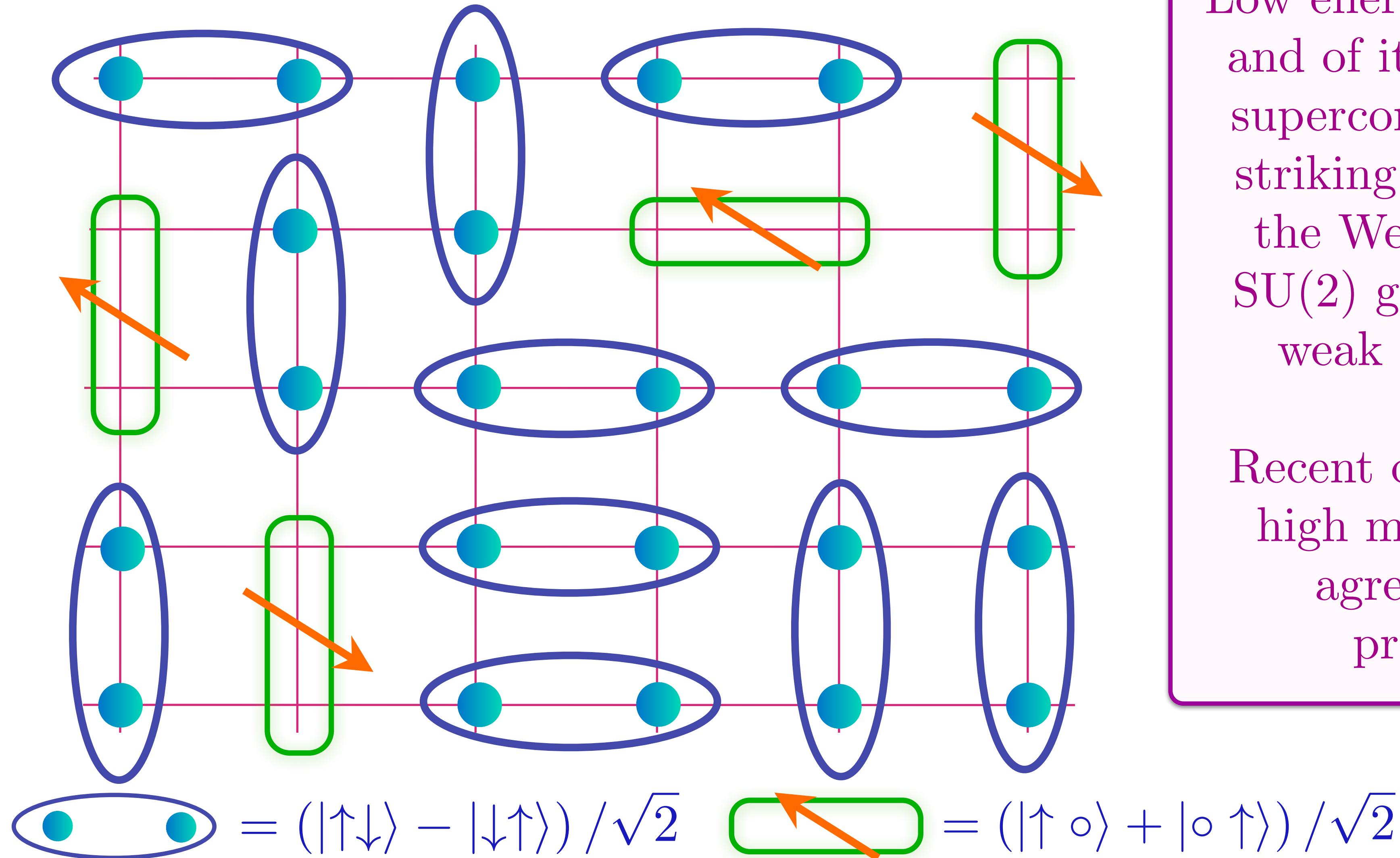


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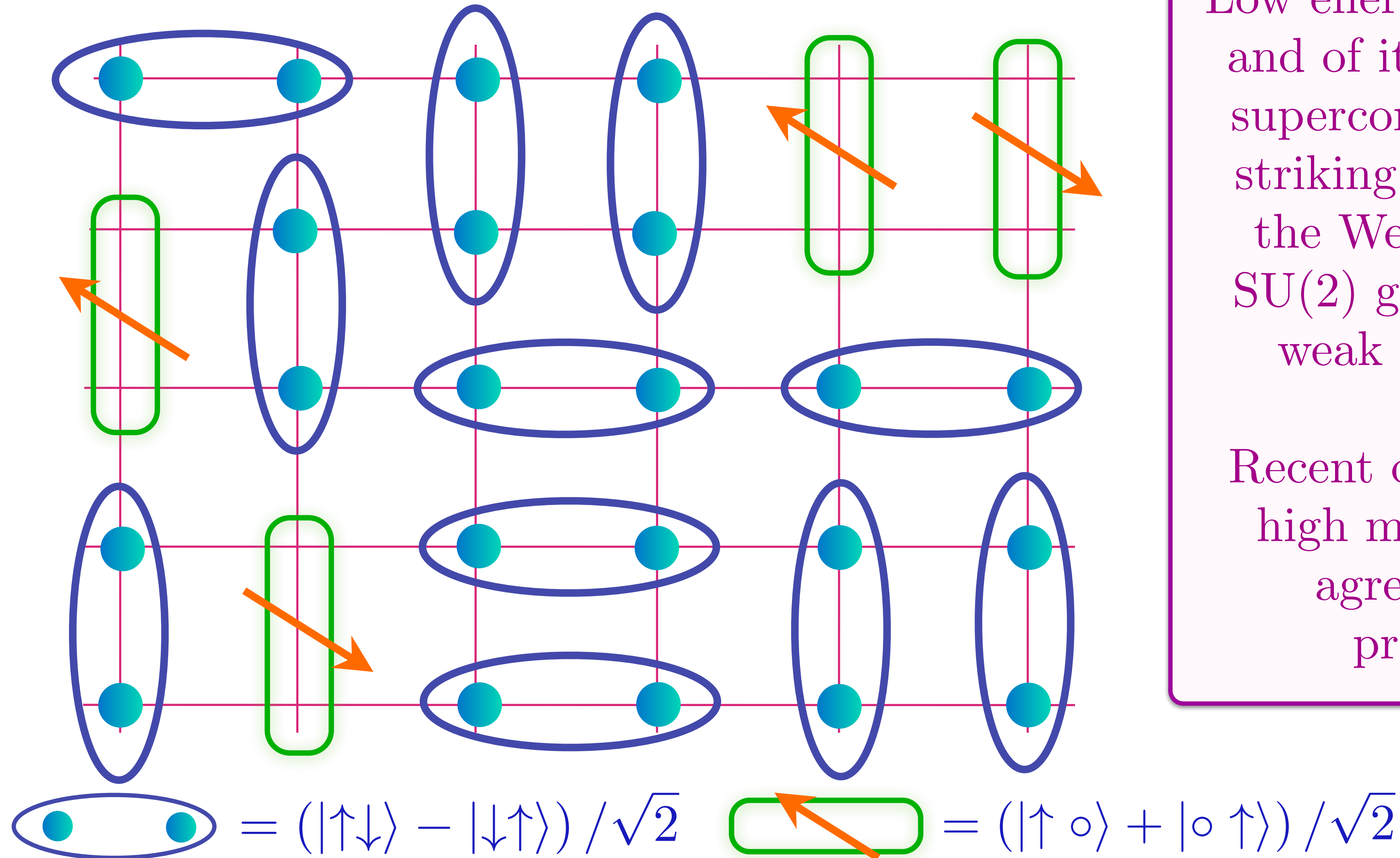


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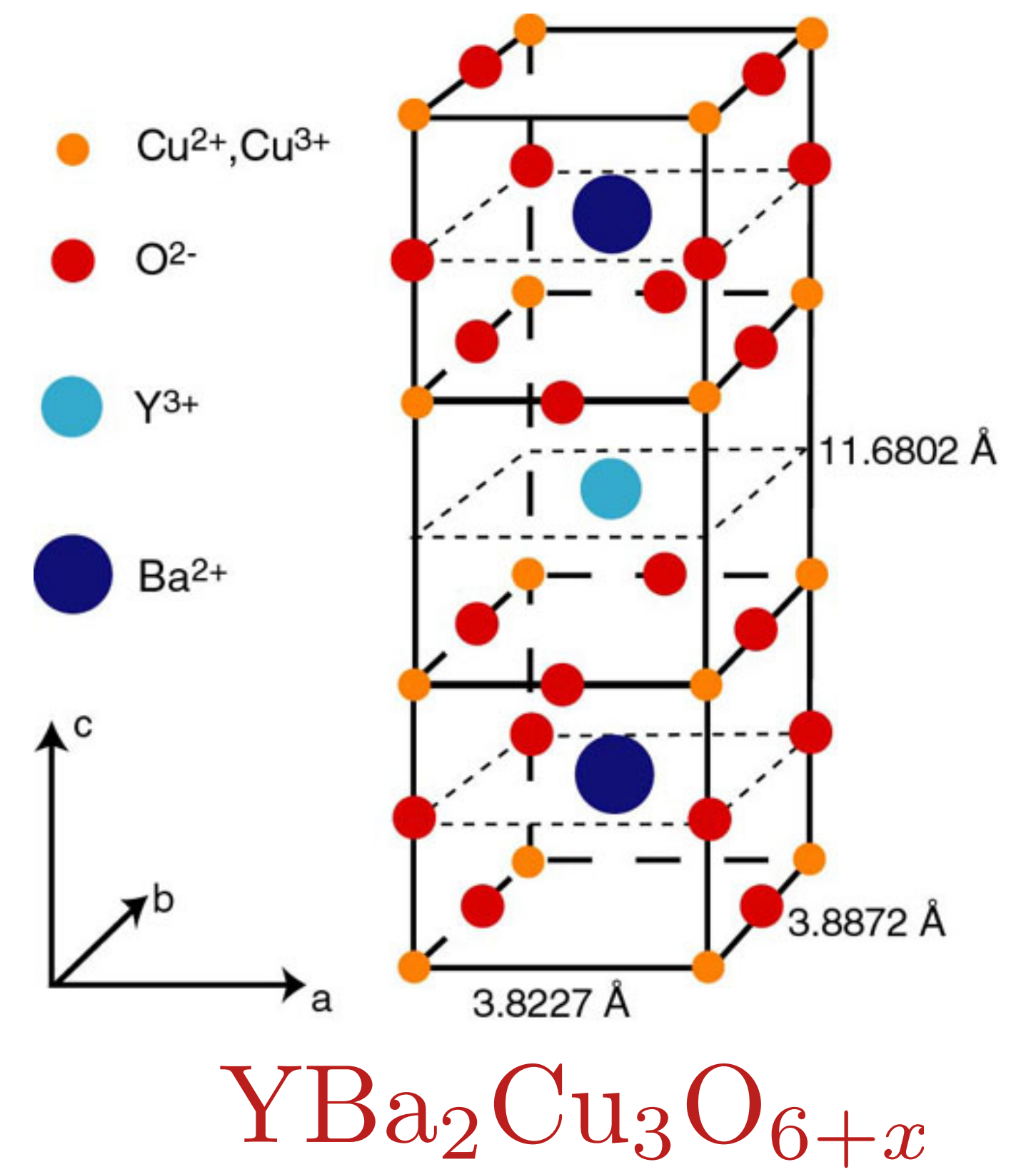
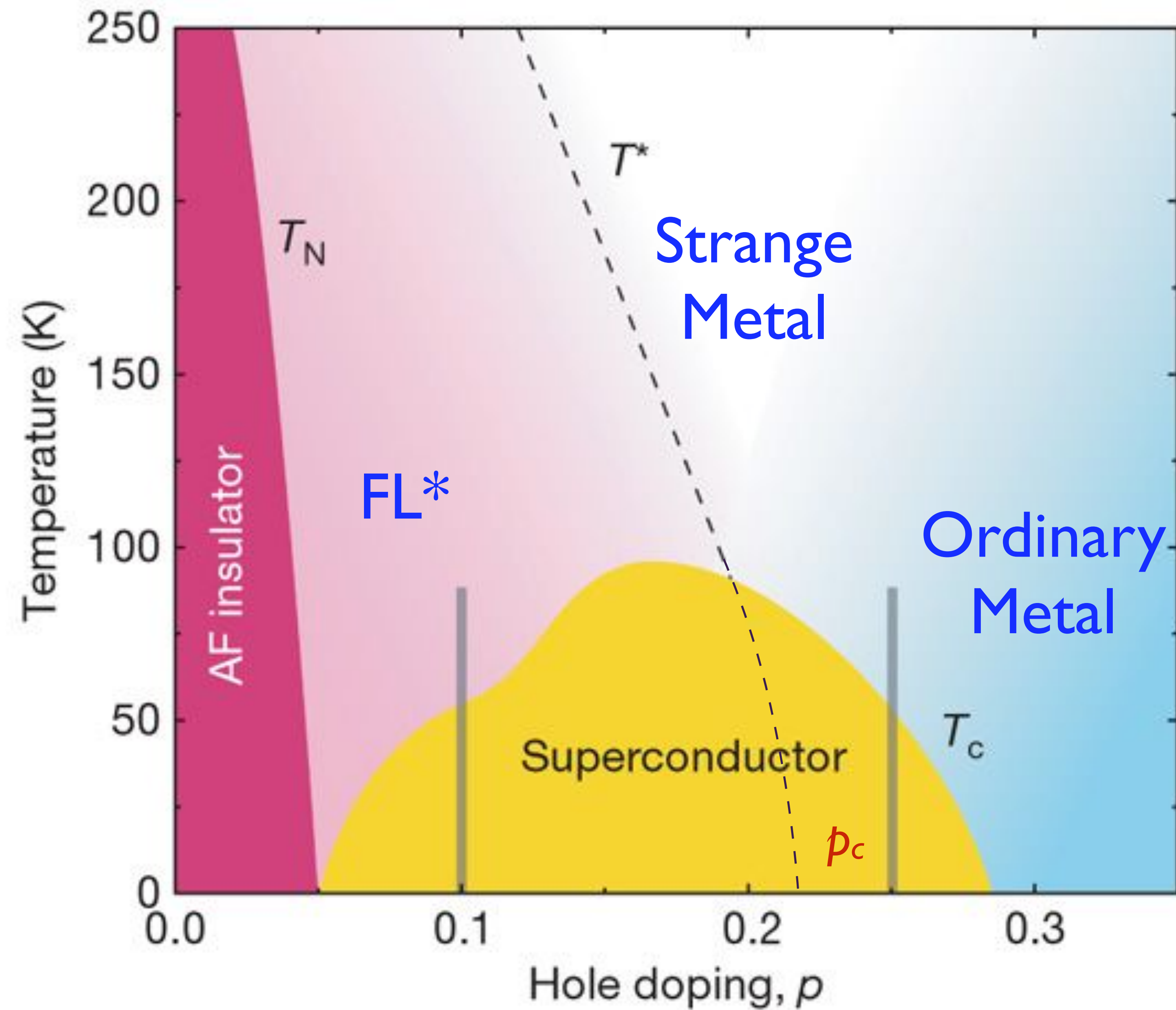
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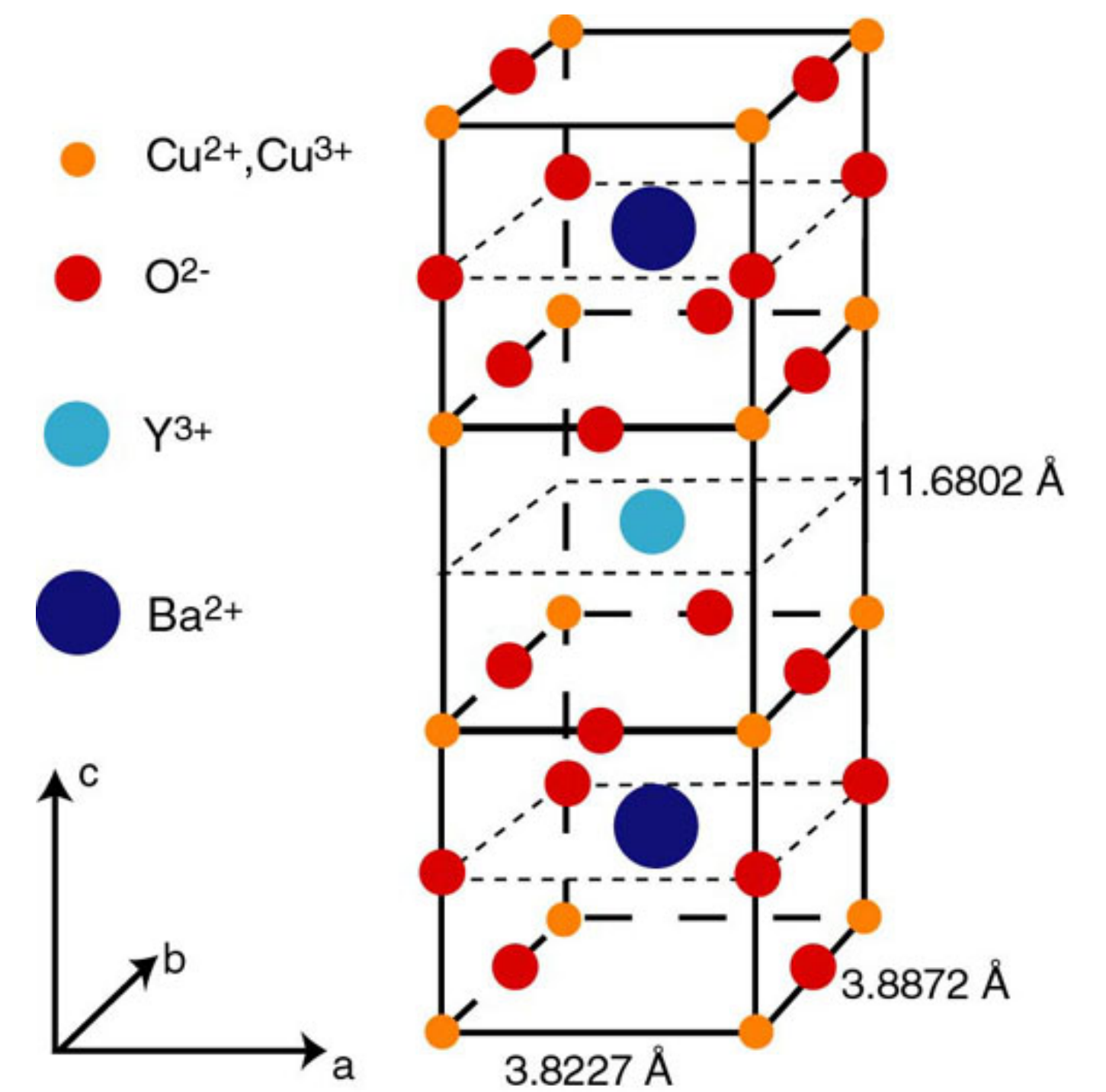
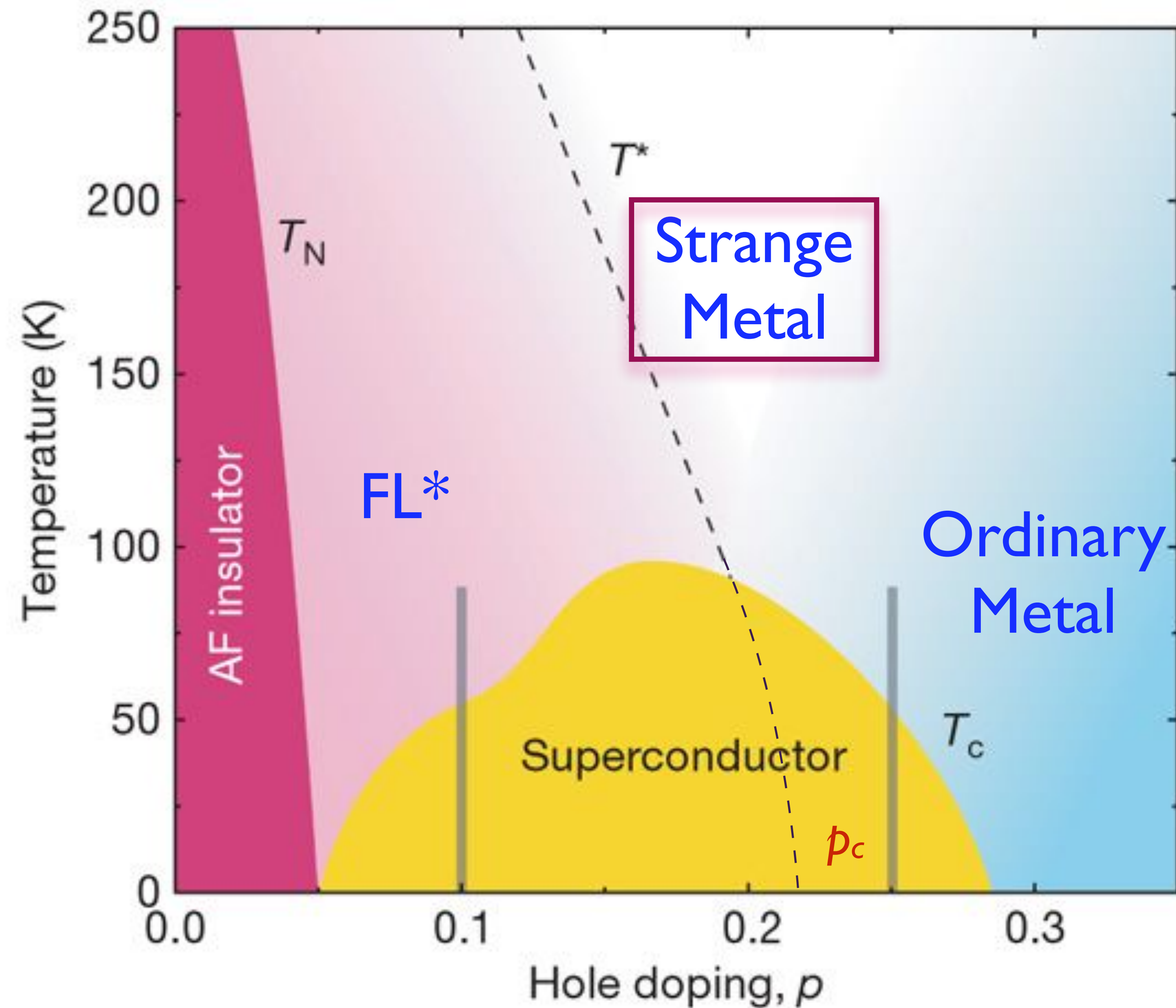
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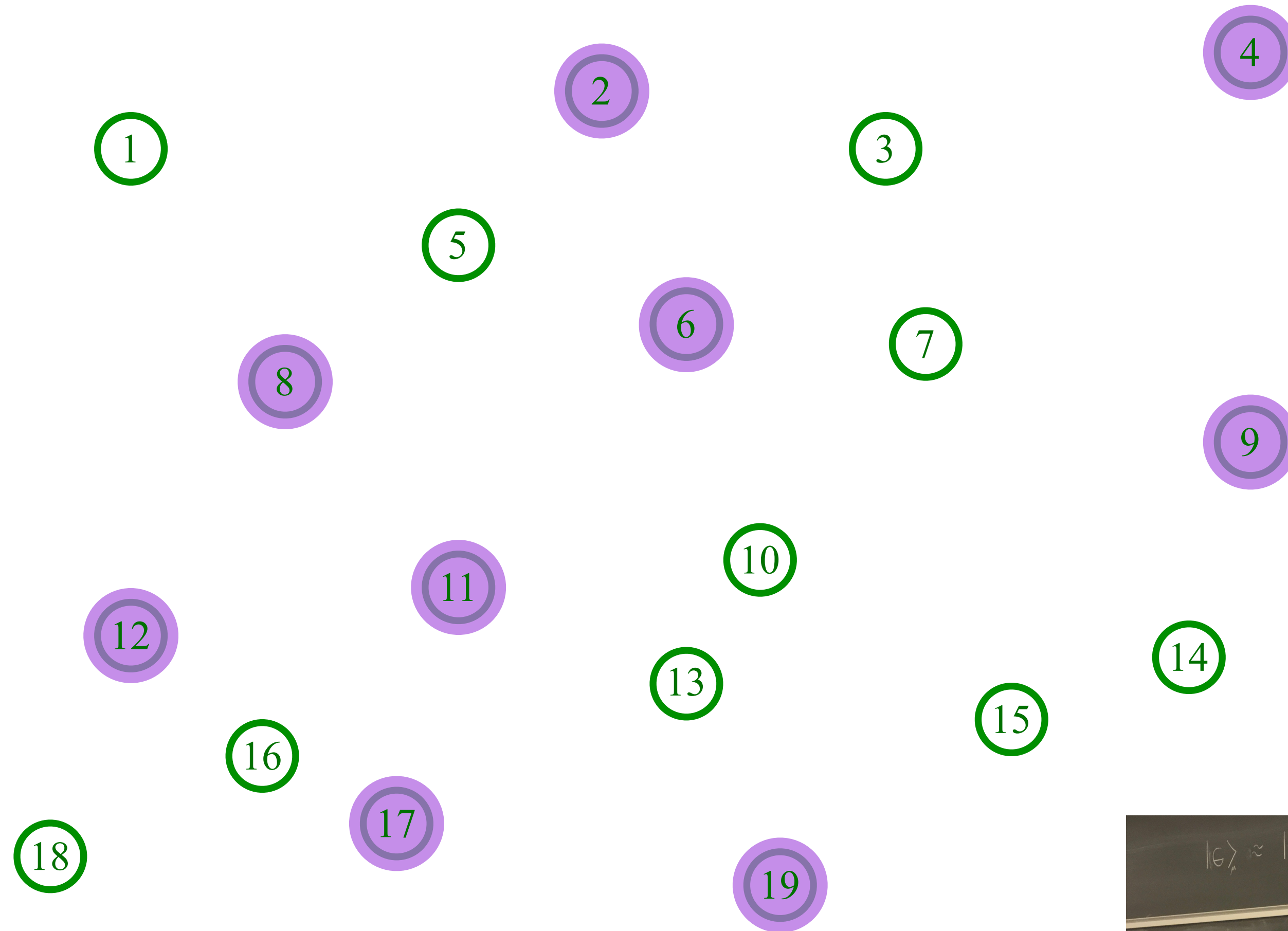


The “strange metal” has no particle-like excitations and is described by a theory of the quantum phase transition from FL* to the ordinary metal: this is a two-dimensional extension of the SYK model

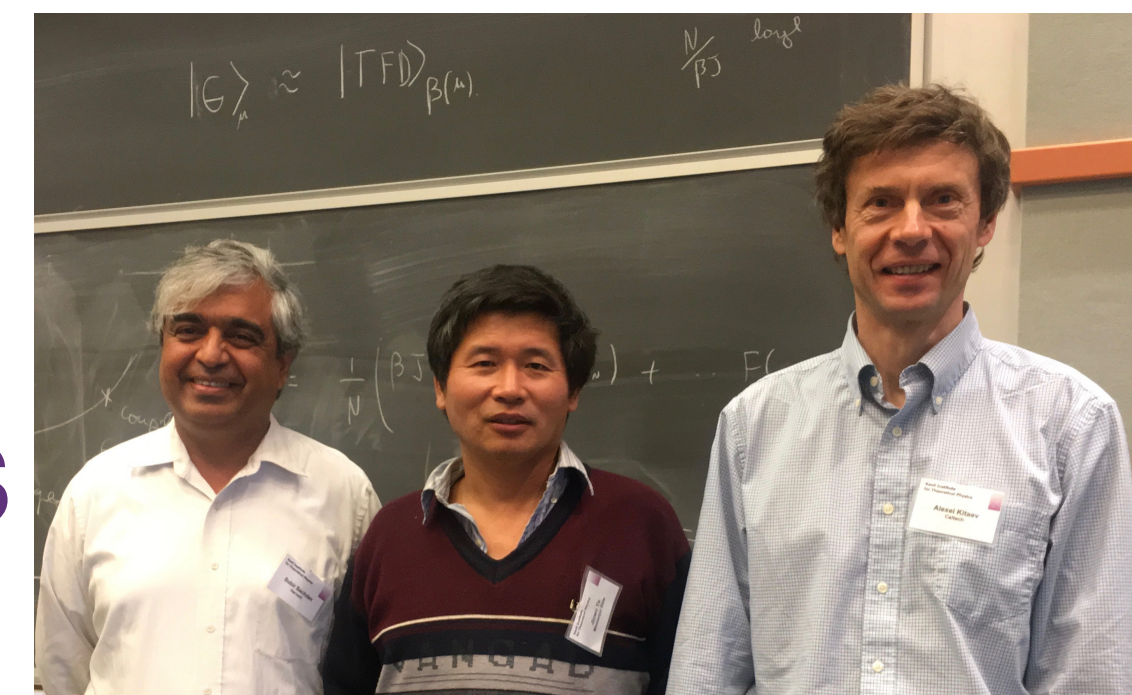
The Sachdev-Ye-Kitaev model
of entanglement of mobile fermions

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



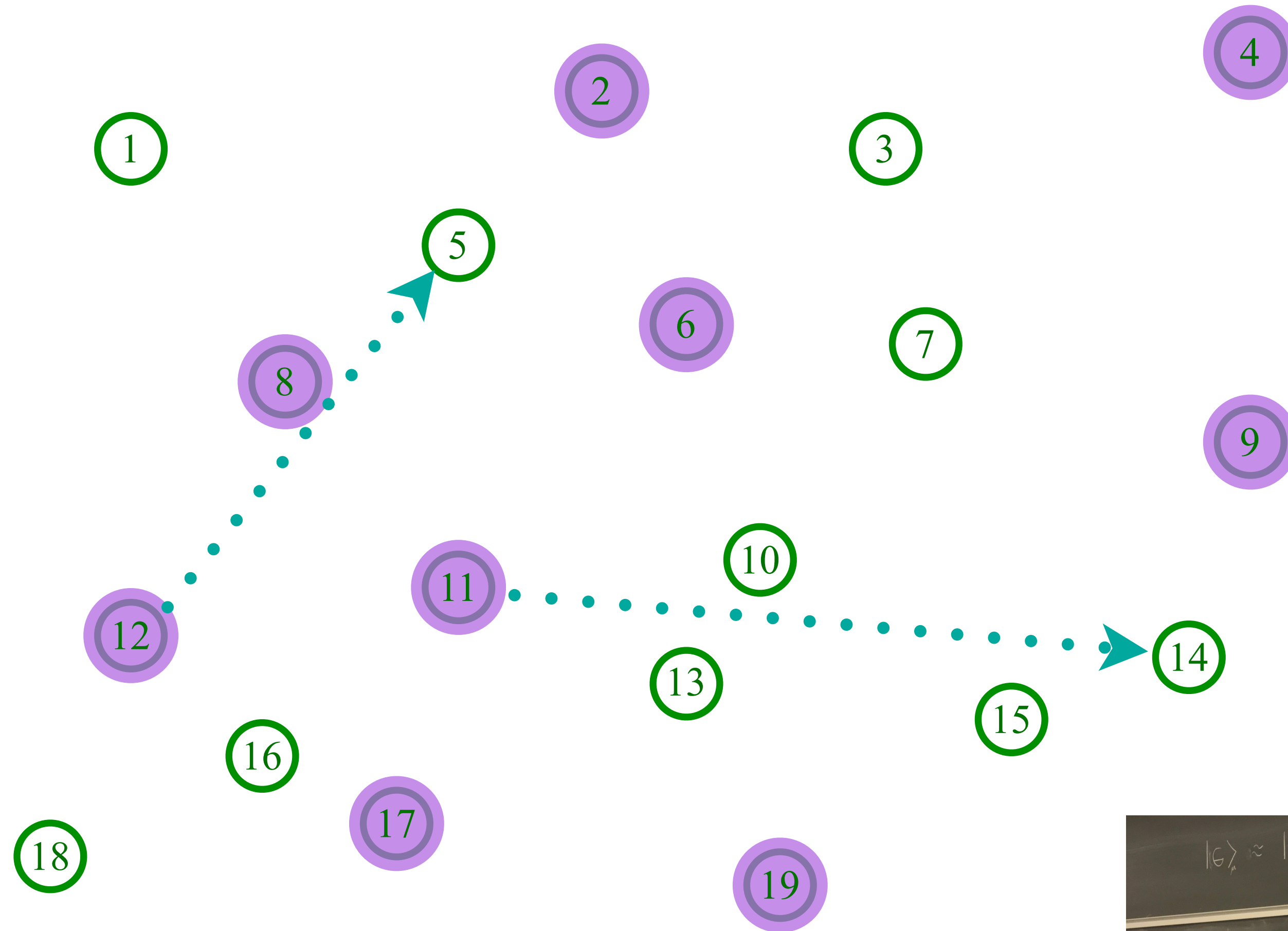
Place electrons randomly on some sites



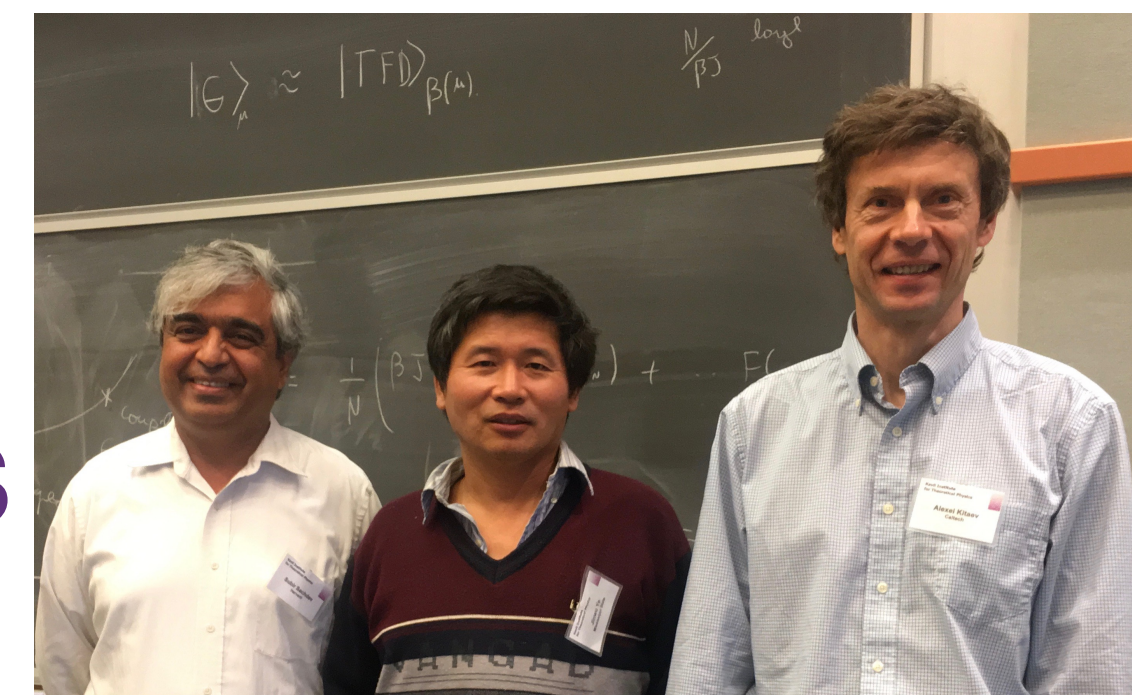
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$$U_{11,12;5,14}$$



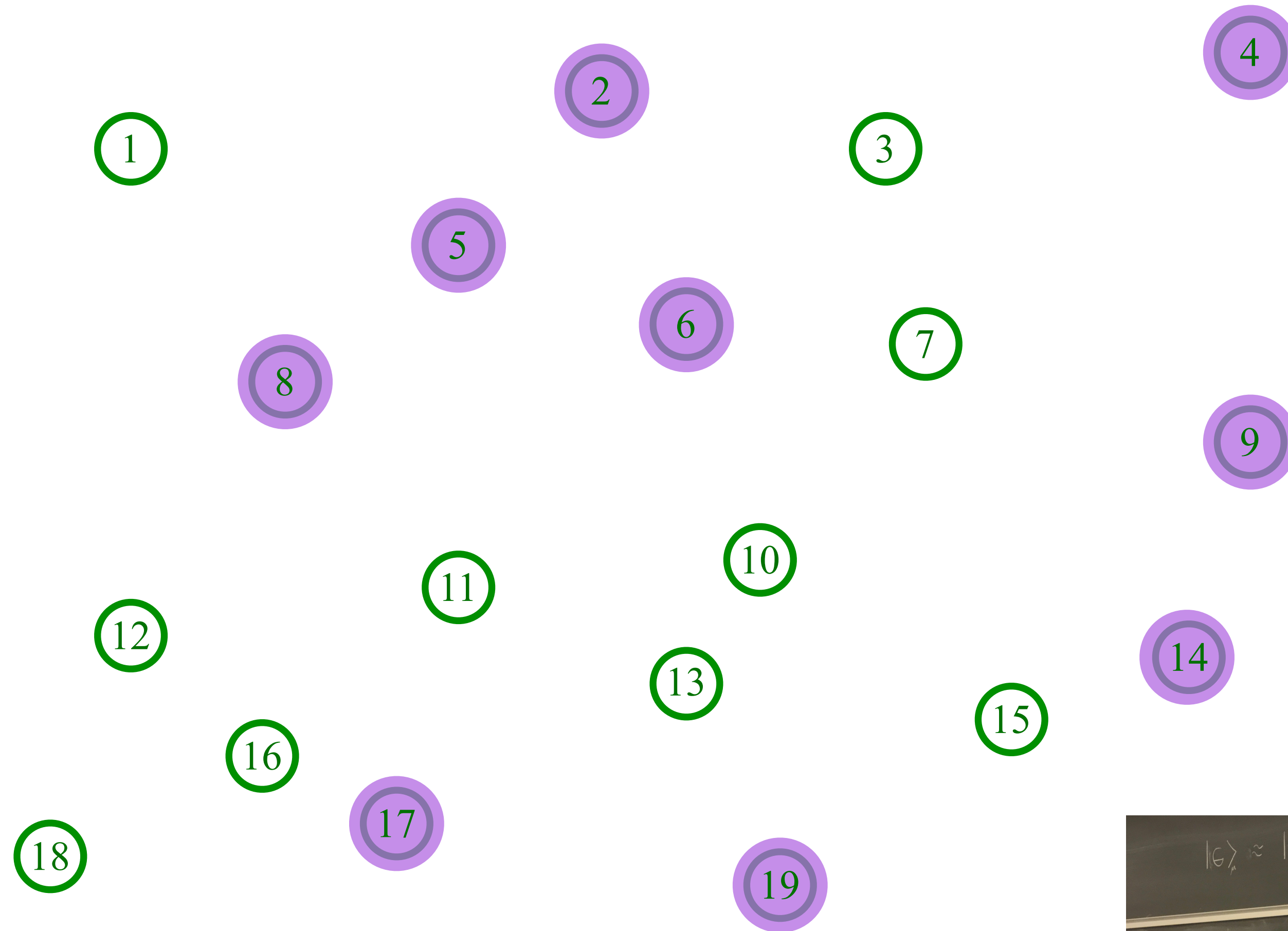
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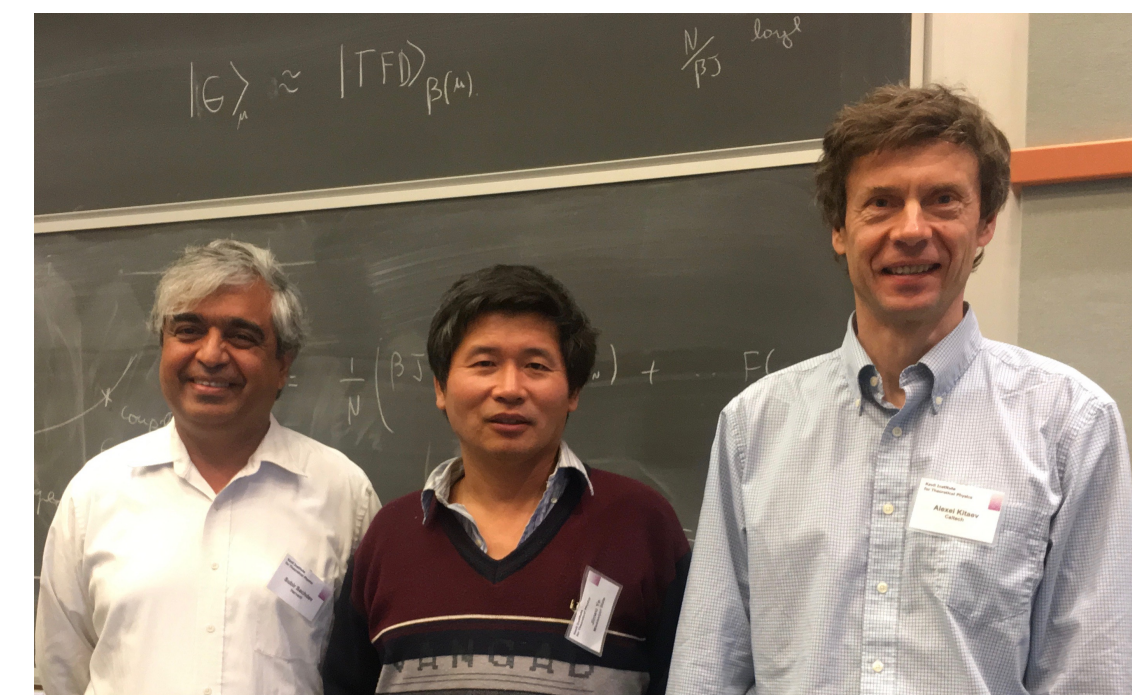
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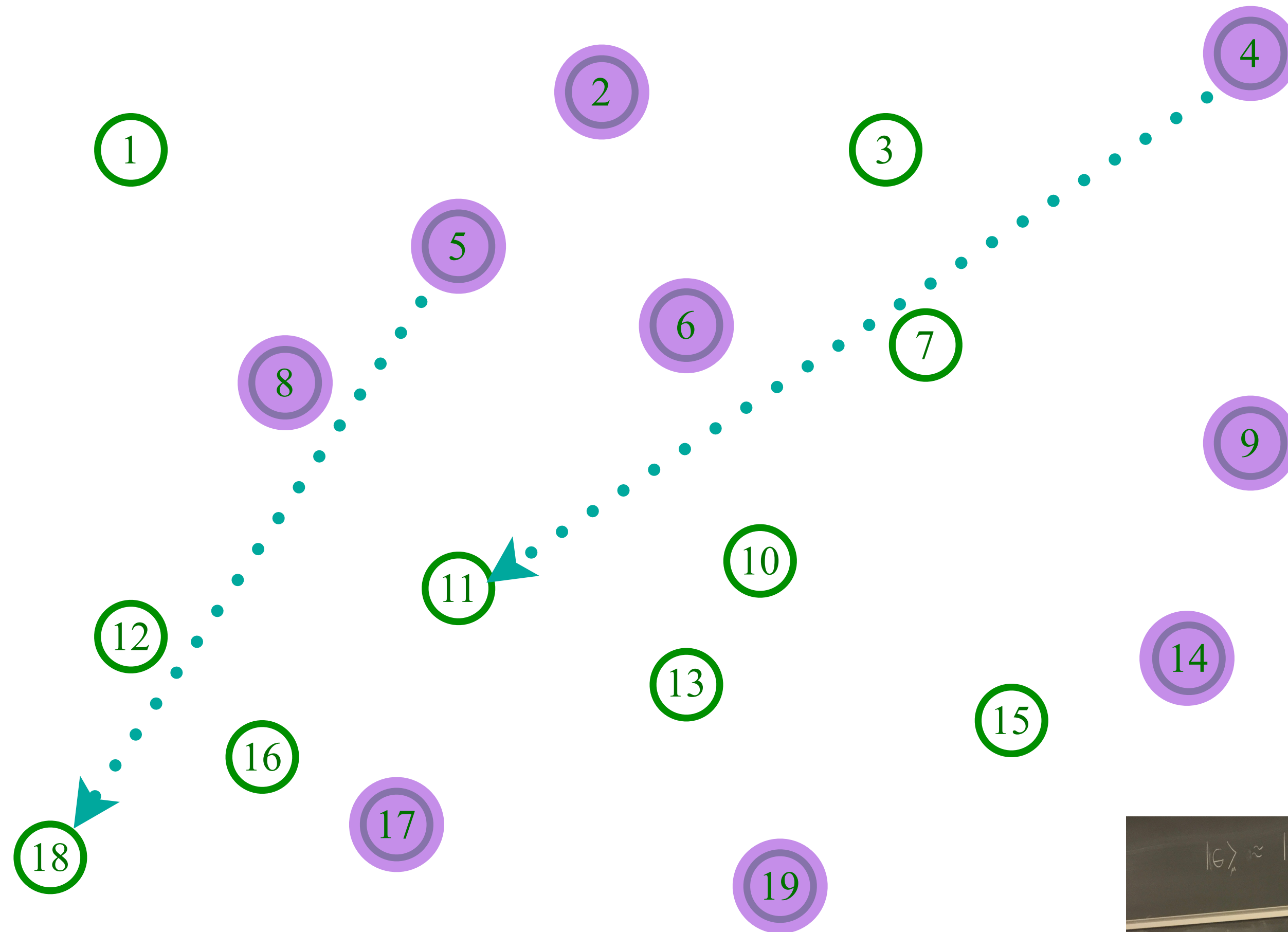
Entangle electrons pairwise randomly



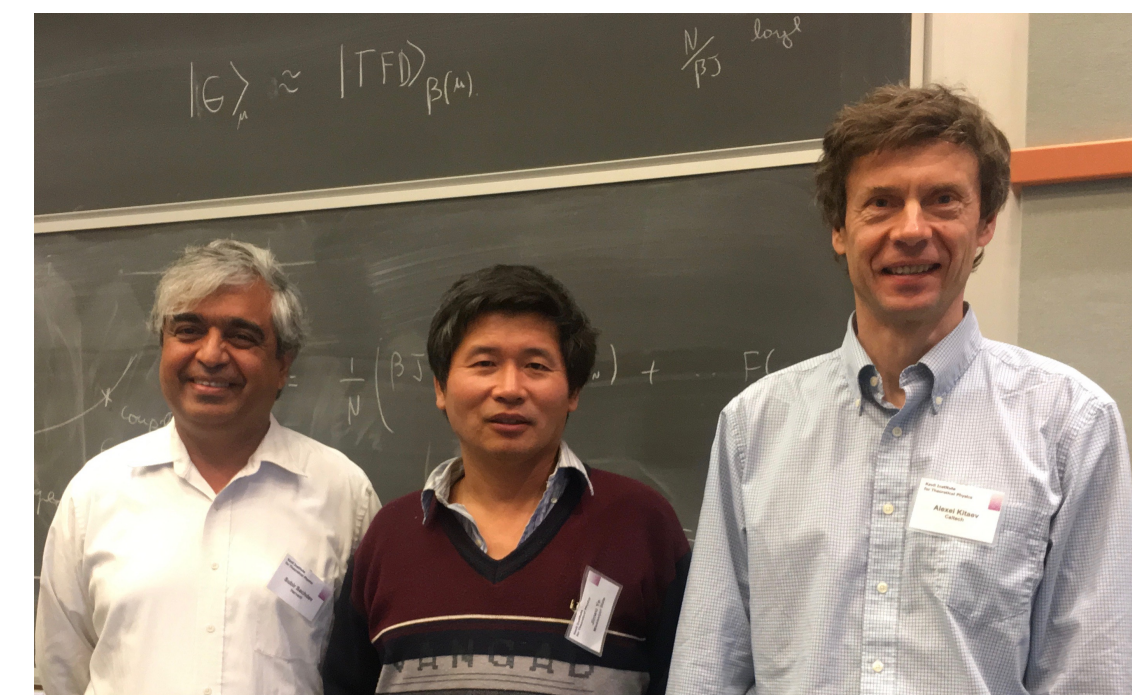
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



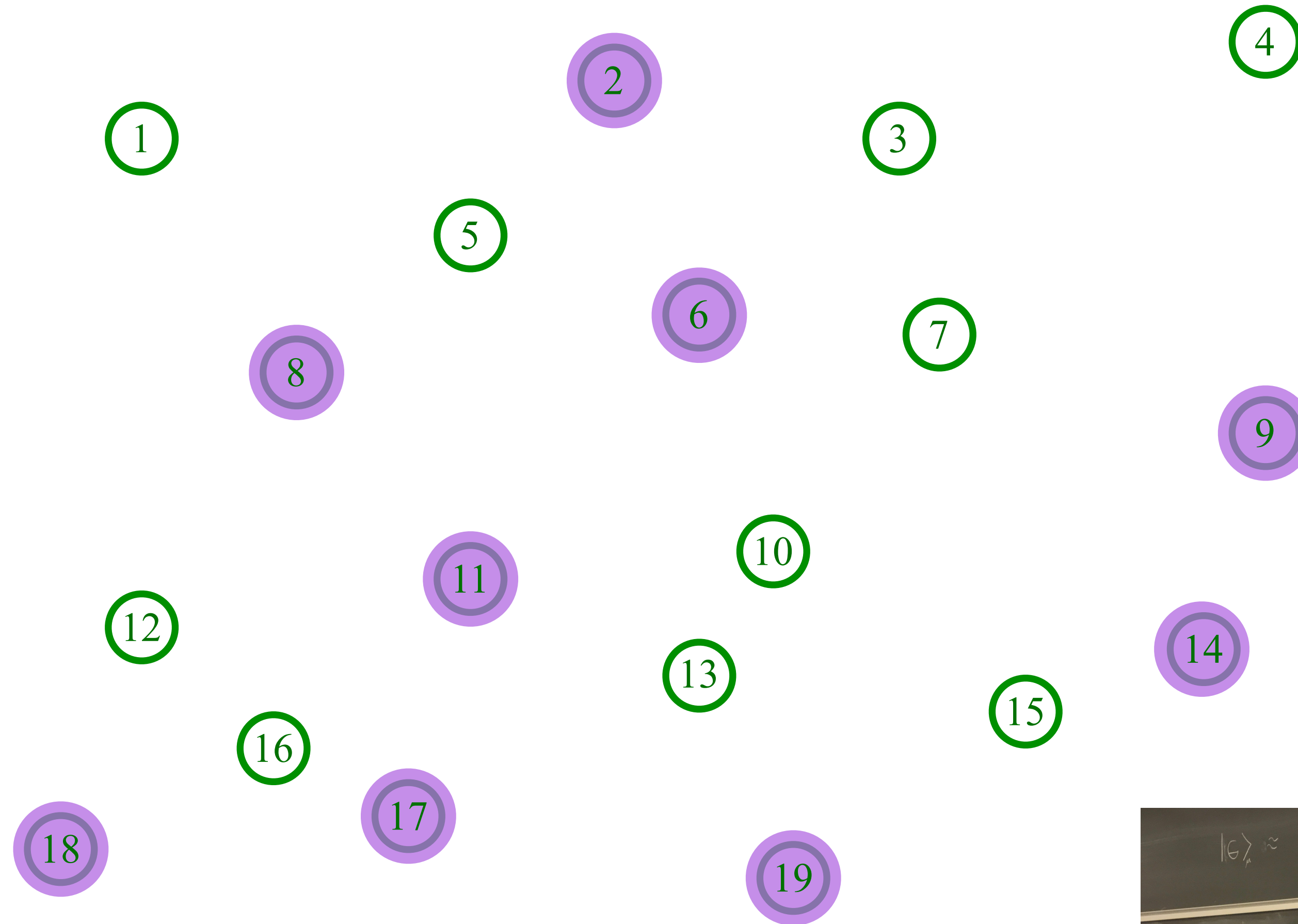
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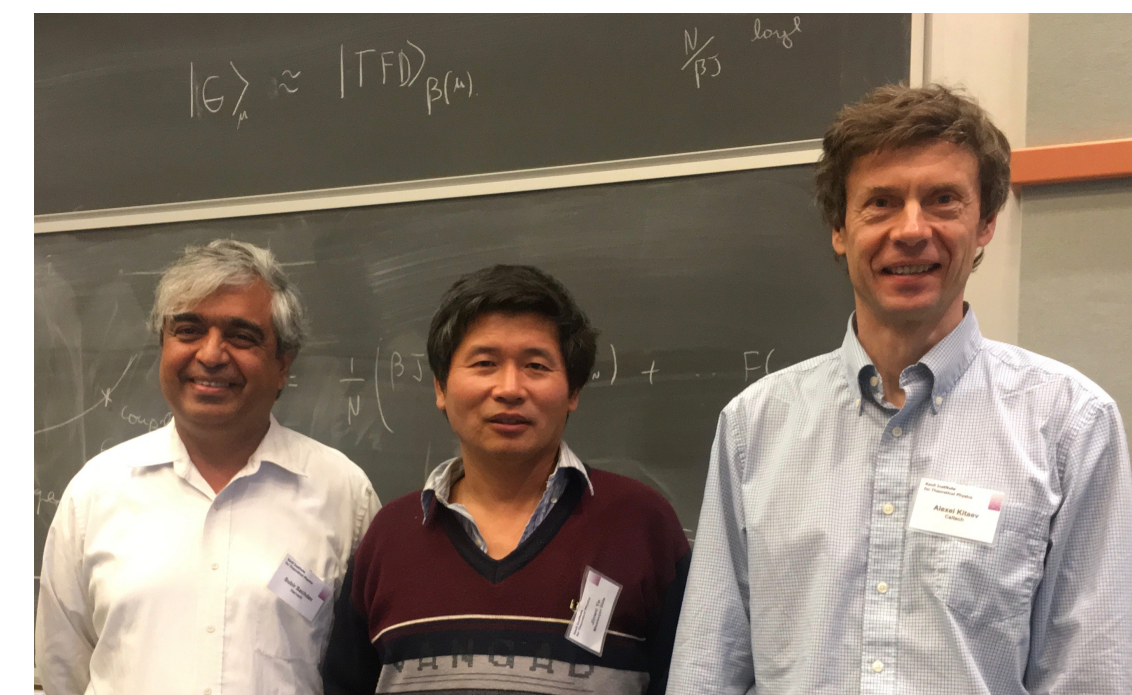
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A solvable model of multi-particle quantum entanglement with mobile fermions.

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A solvable model of multi-particle quantum entanglement with mobile fermions.

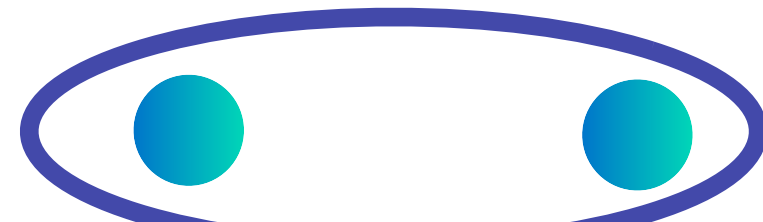
Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons....

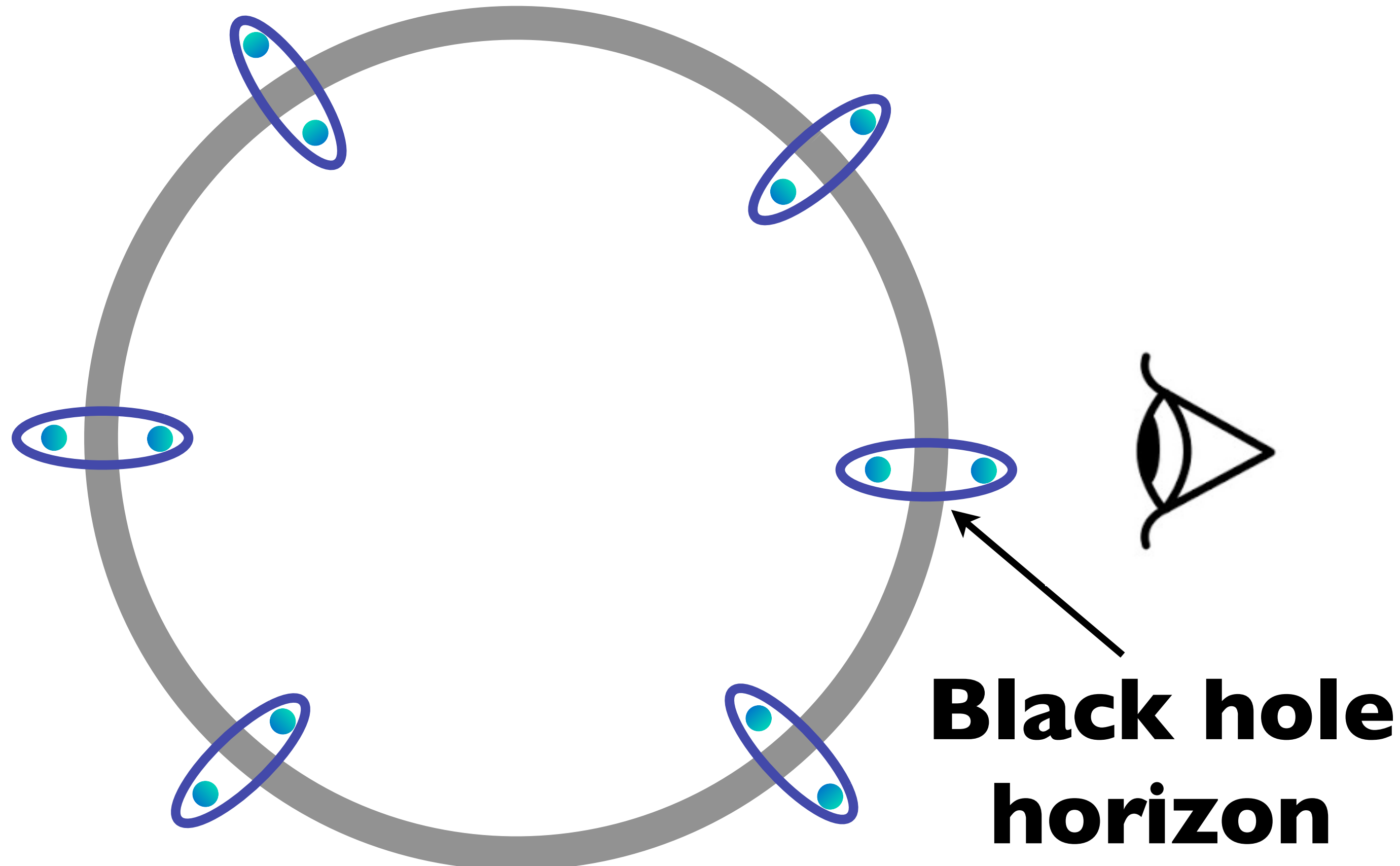
Current is carried by an “entangled quantum soup”

Quantum entanglement,
the SYK model,
and black holes

Quantum Entanglement across a black hole horizon

Quantum entanglement
on the surface


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



By computations *outside*
the black hole,
Hawking obtained
the black hole entropy

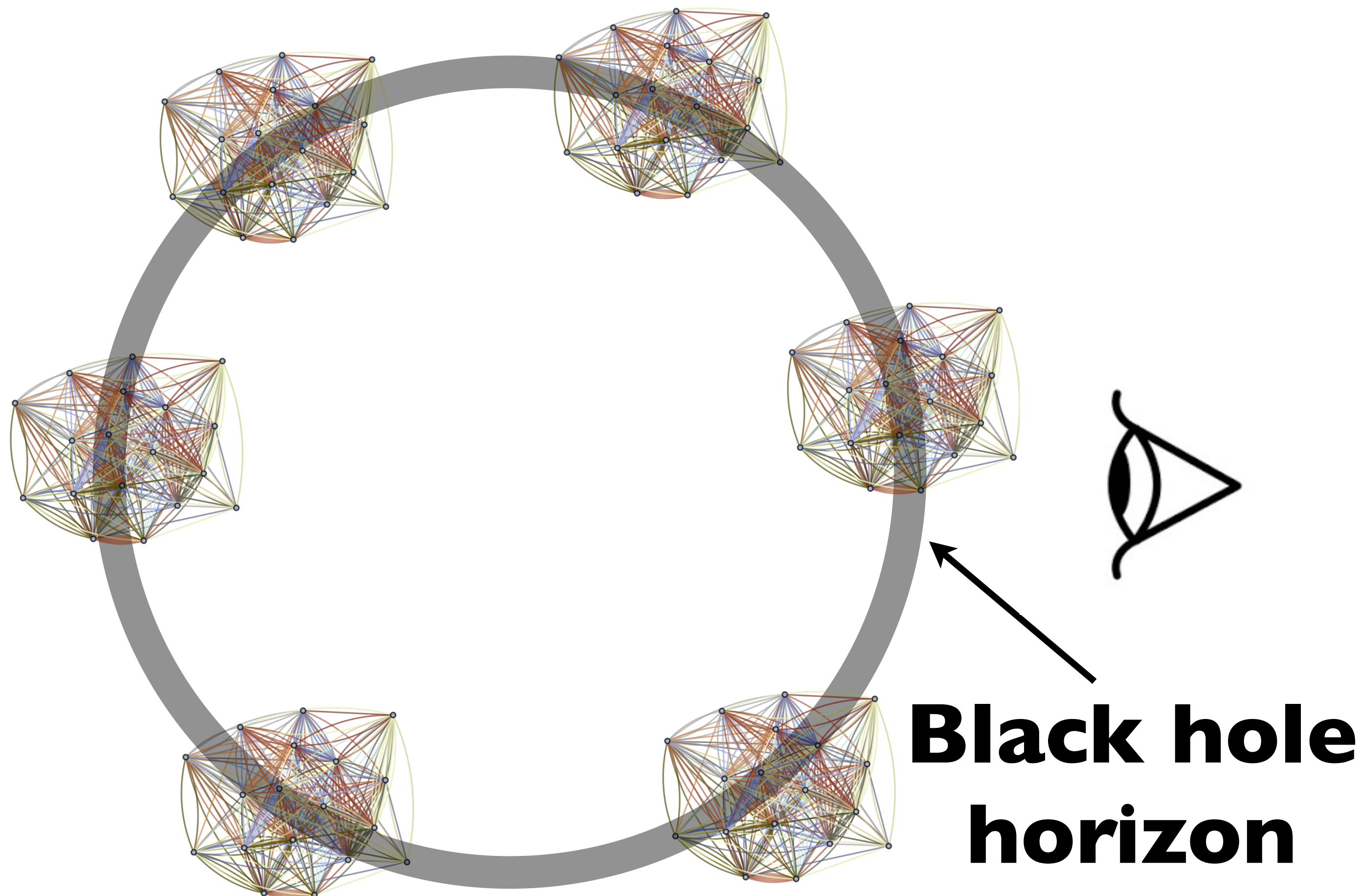
$$S = \frac{Ac^3}{4G\hbar}$$

where A is area of the
black hole horizon.

All other systems have
entropy proportional to
their volume.

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Quantum entanglement
on the surface



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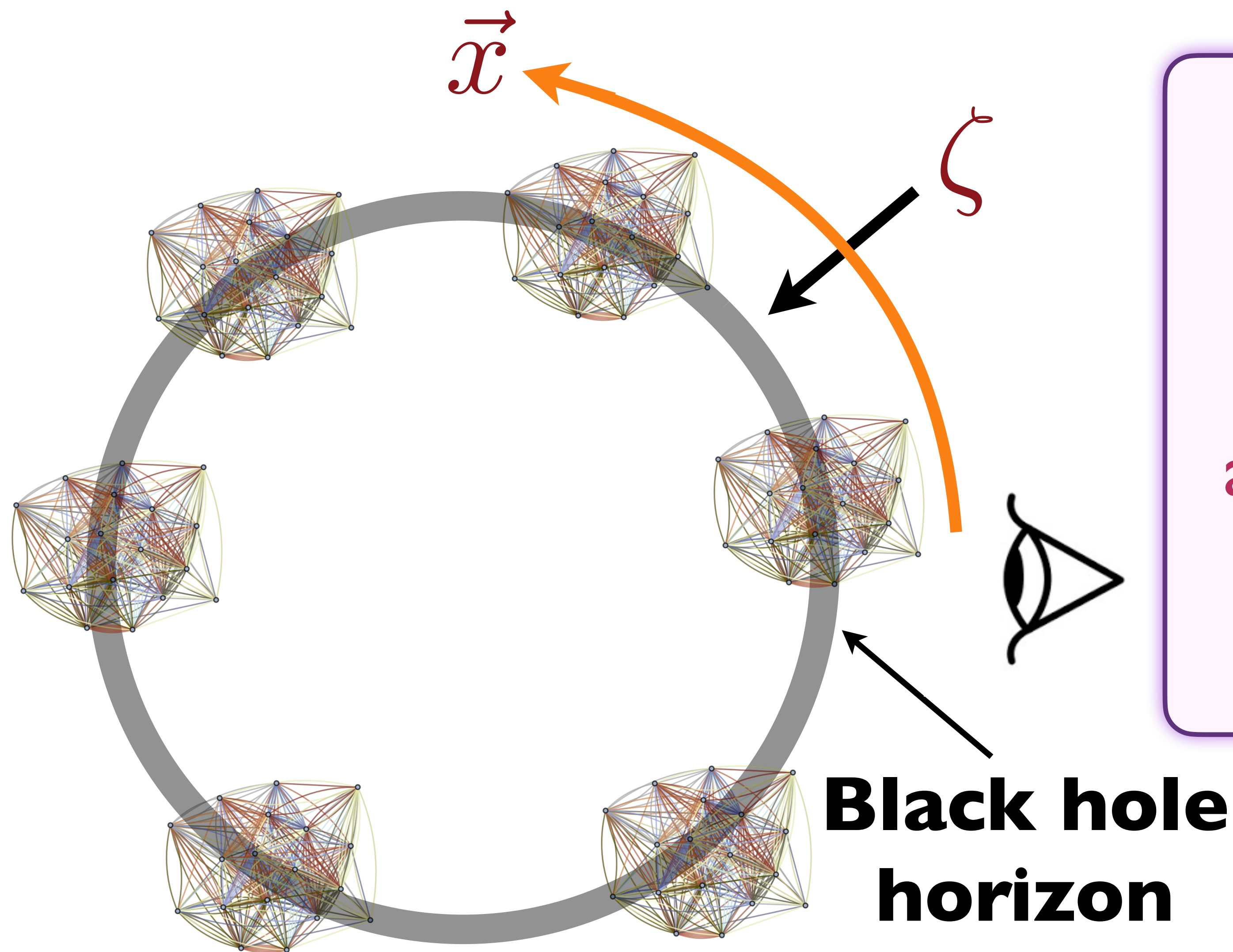
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Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge

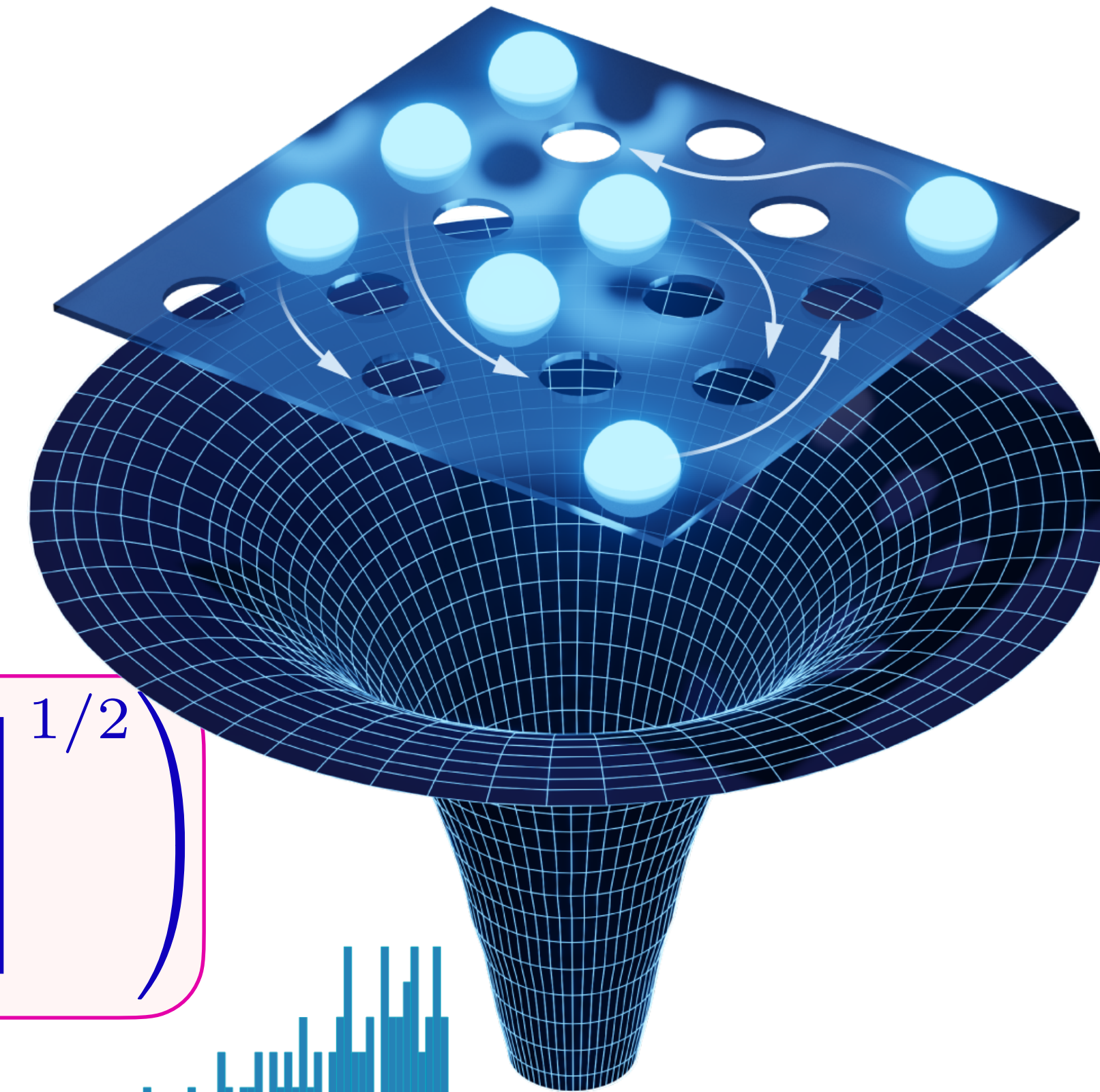


The quantum versions of
Maxwell's and Einstein's
equations in
 ζ space and time are
also the equations describing
electron entanglement
in the SYK model!

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 Q ($A_0 = 2GQ^2/c^4$), the density of quantum states at small energy E is

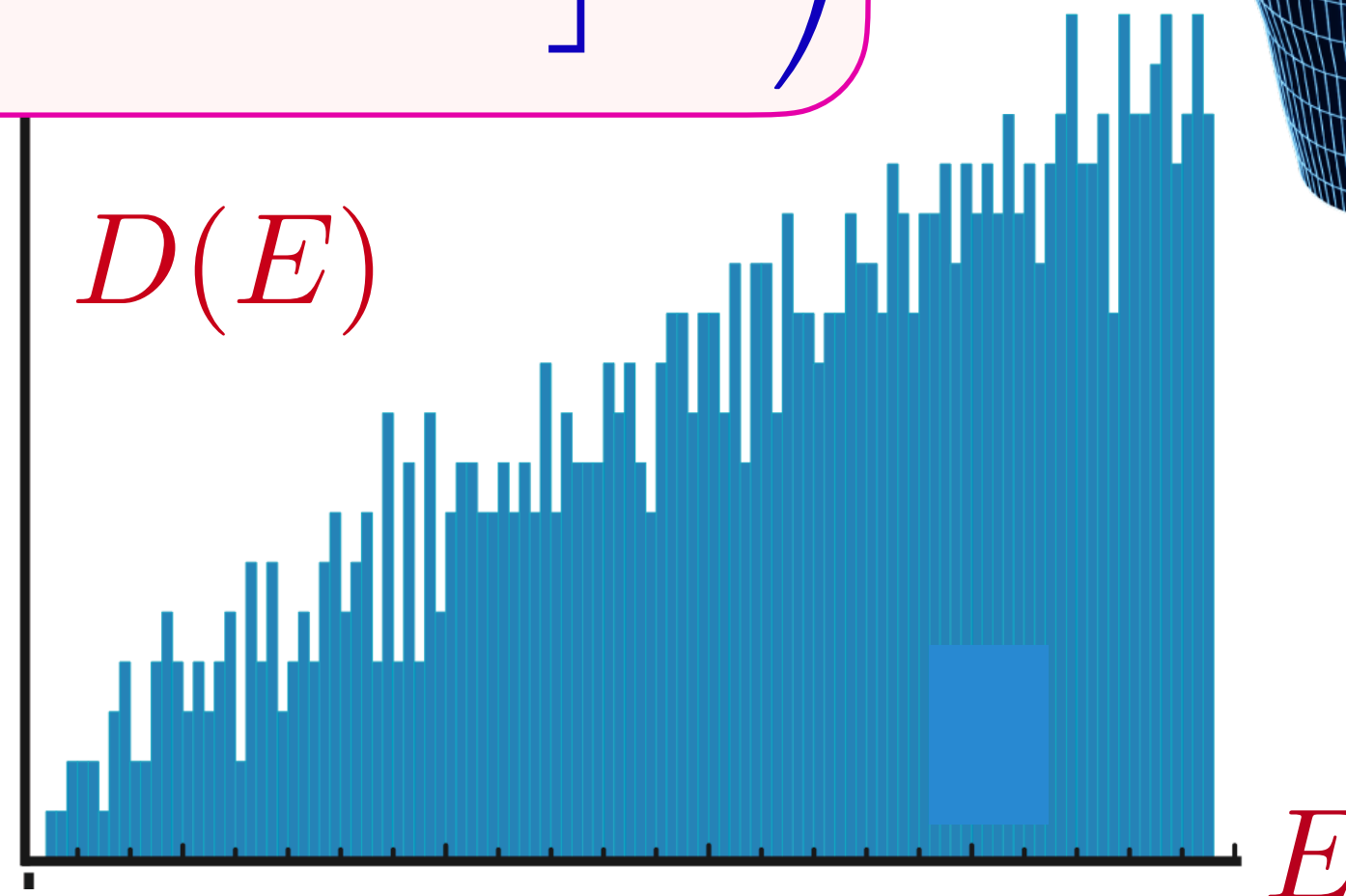
$$D(E) \sim \left(\frac{A_0 c^3}{\hbar G} \right)^{-347/90} \exp \left(\frac{A_0 c^3}{4\hbar G} \right) \sinh \left(\left[\frac{\sqrt{\pi} A_0^{3/2} c^2}{\hbar^2 G} E \right]^{1/2} \right)$$



Bekenstein-Hawking

Iliesiu, Murthy, Turiaci (2022)

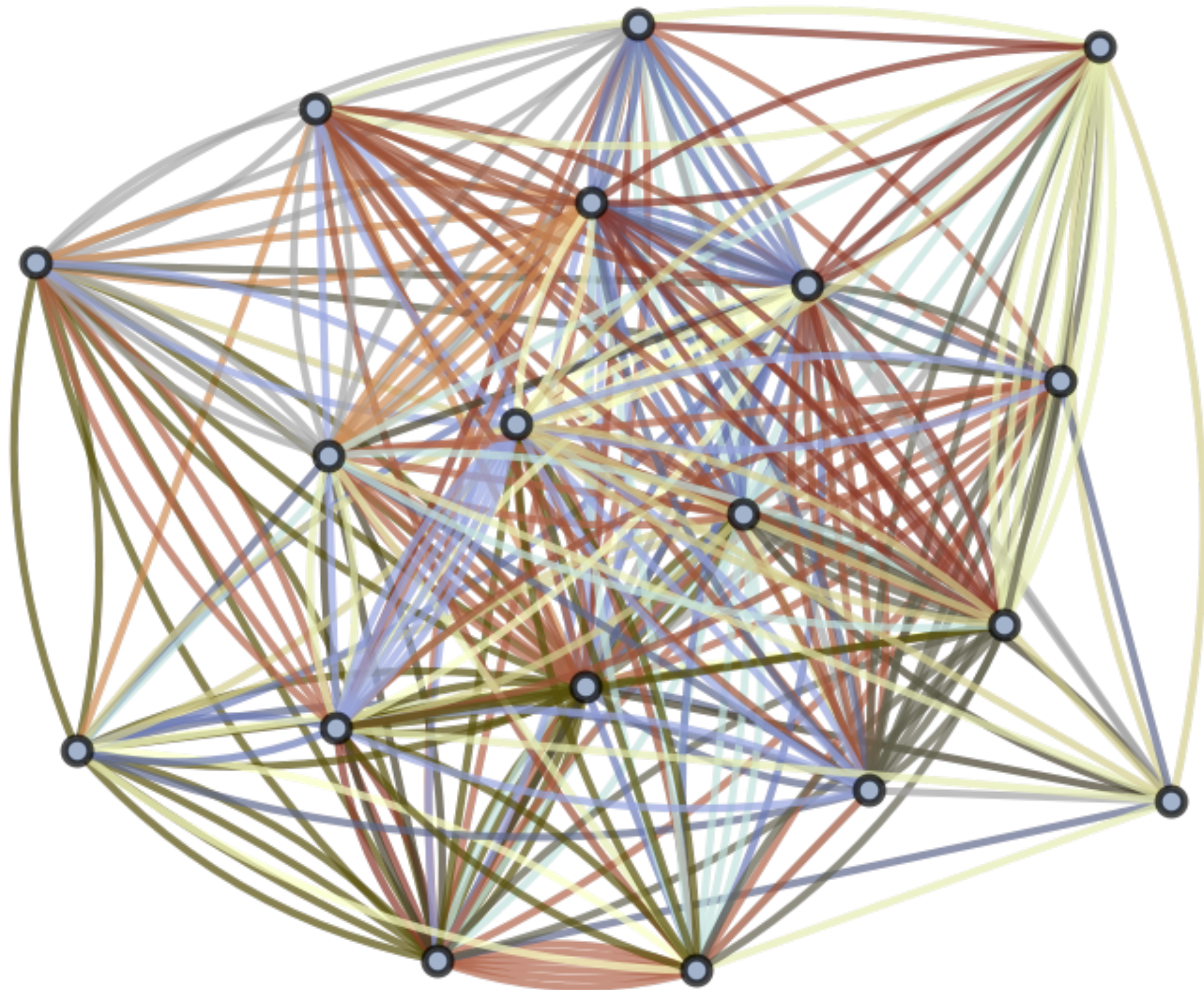
Developments from the SYK model



Similar remarks apply to rotating neutral black holes.

The Sachdev-Ye-Kitaev (SYK) model

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

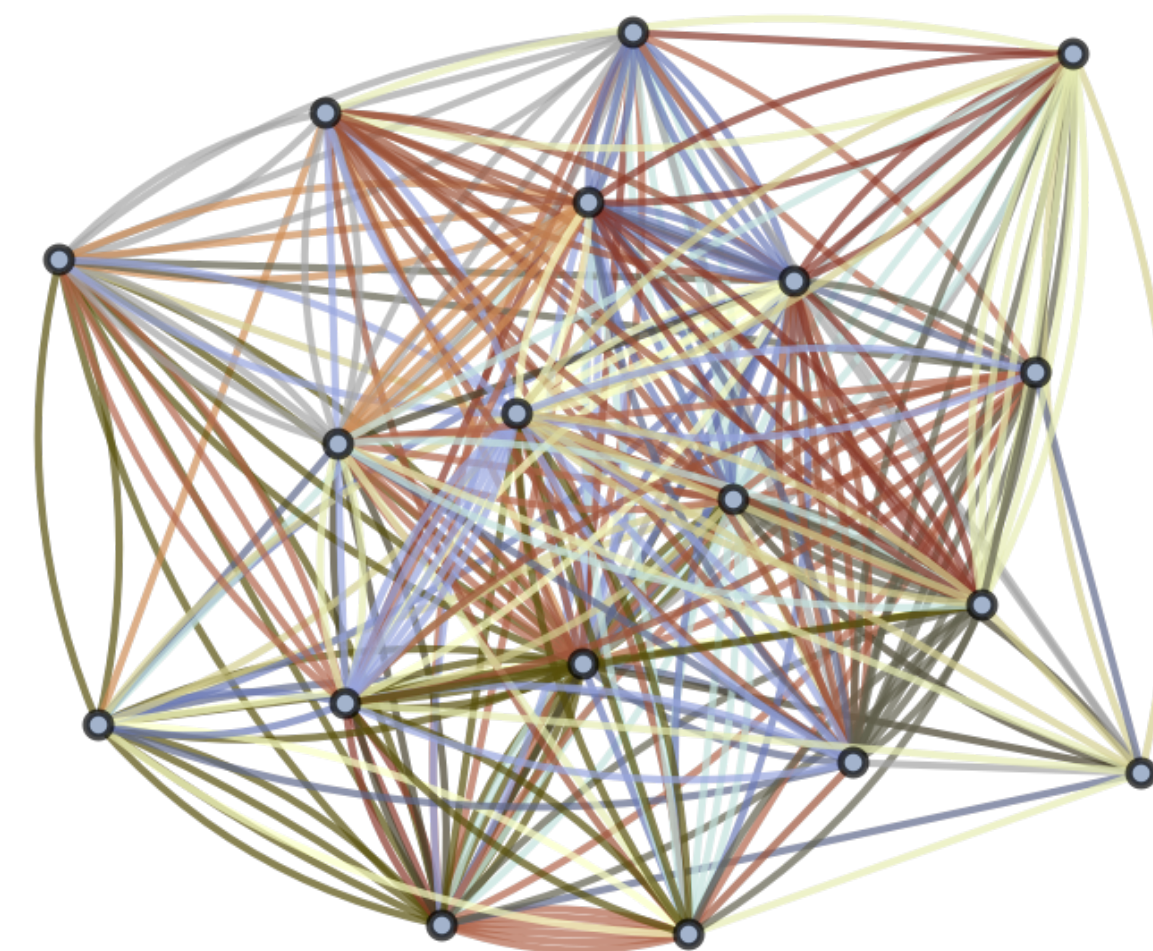
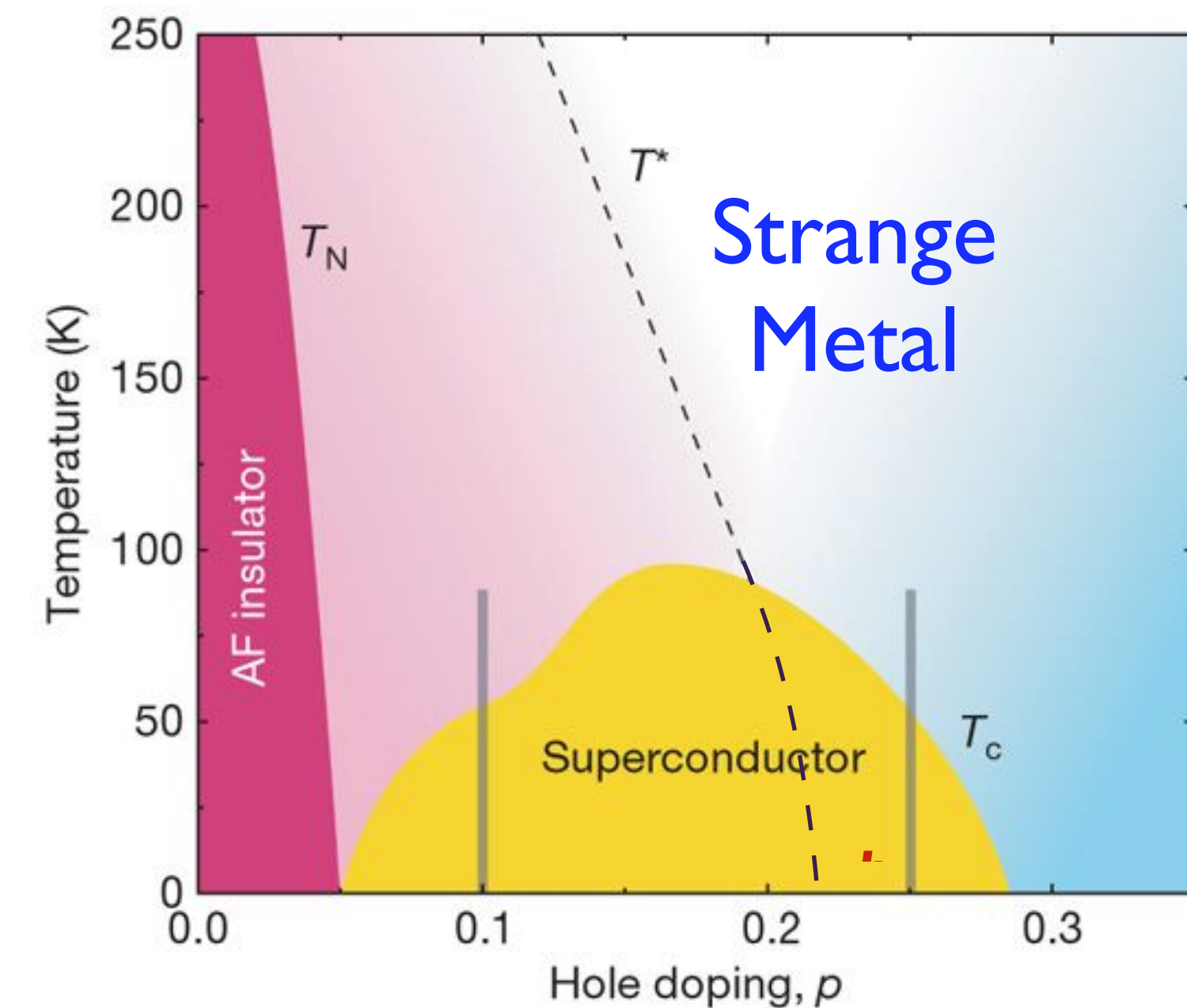


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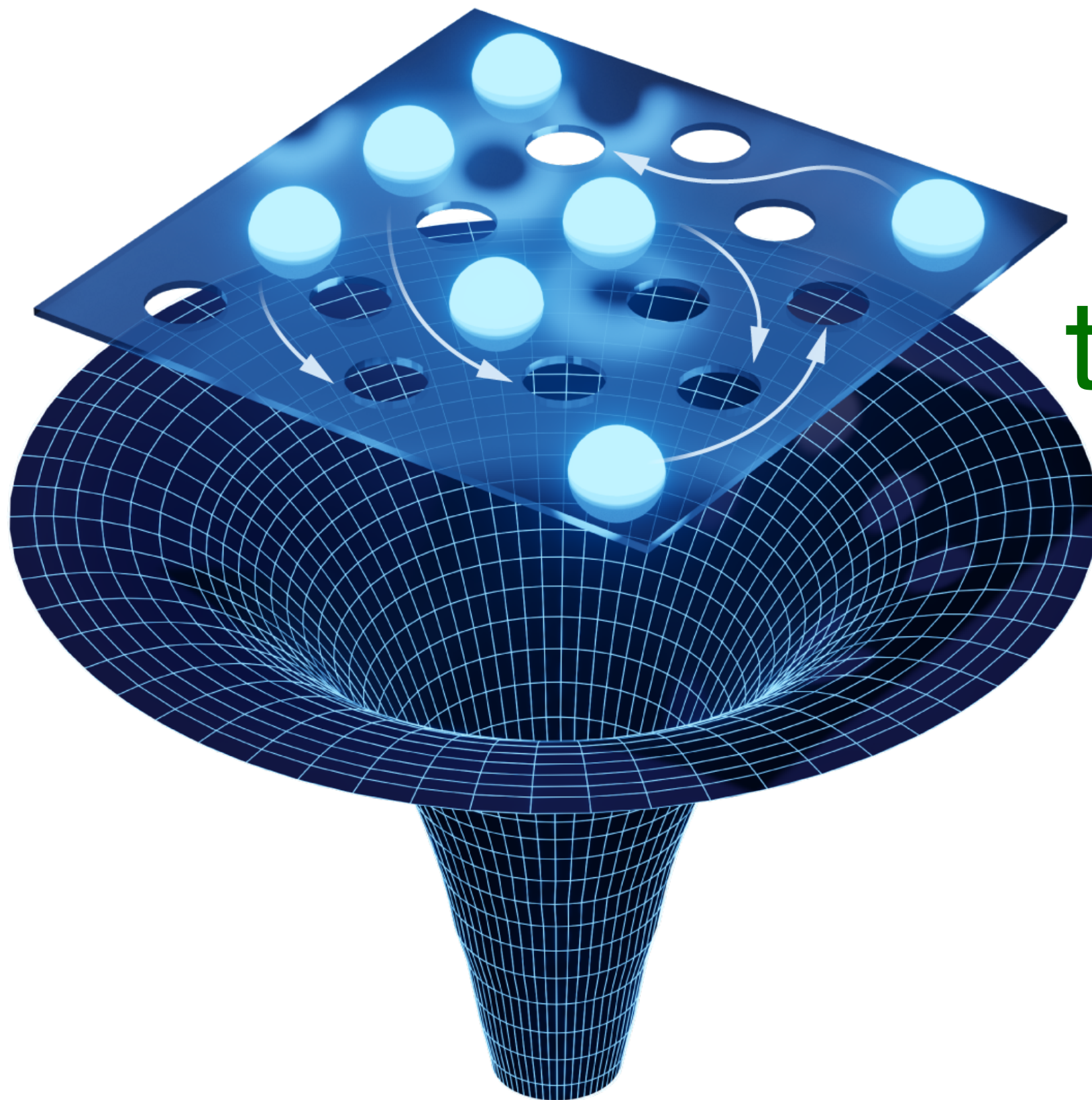
In one set of variables, it helps describe the *strange* electrical properties of YBCO

Sachdev, Ye (1993)



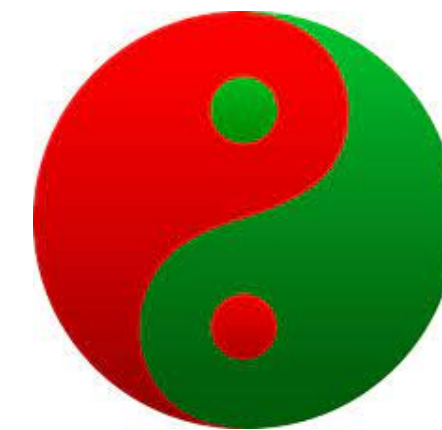
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In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



In a ***dual*** set of variables it describes the interior of ***charged black holes***

Sachdev (2010), Kitaev (2015), Maldacena Stanford (2015)