

# Quantum entanglement at all distances

May 6, 2022

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Maureen and John Henricks Distinguished Visiting Professor,  
Institute for Advanced Studies, Princeton



INSTITUTE FOR  
ADVANCED STUDY

PHYSICS

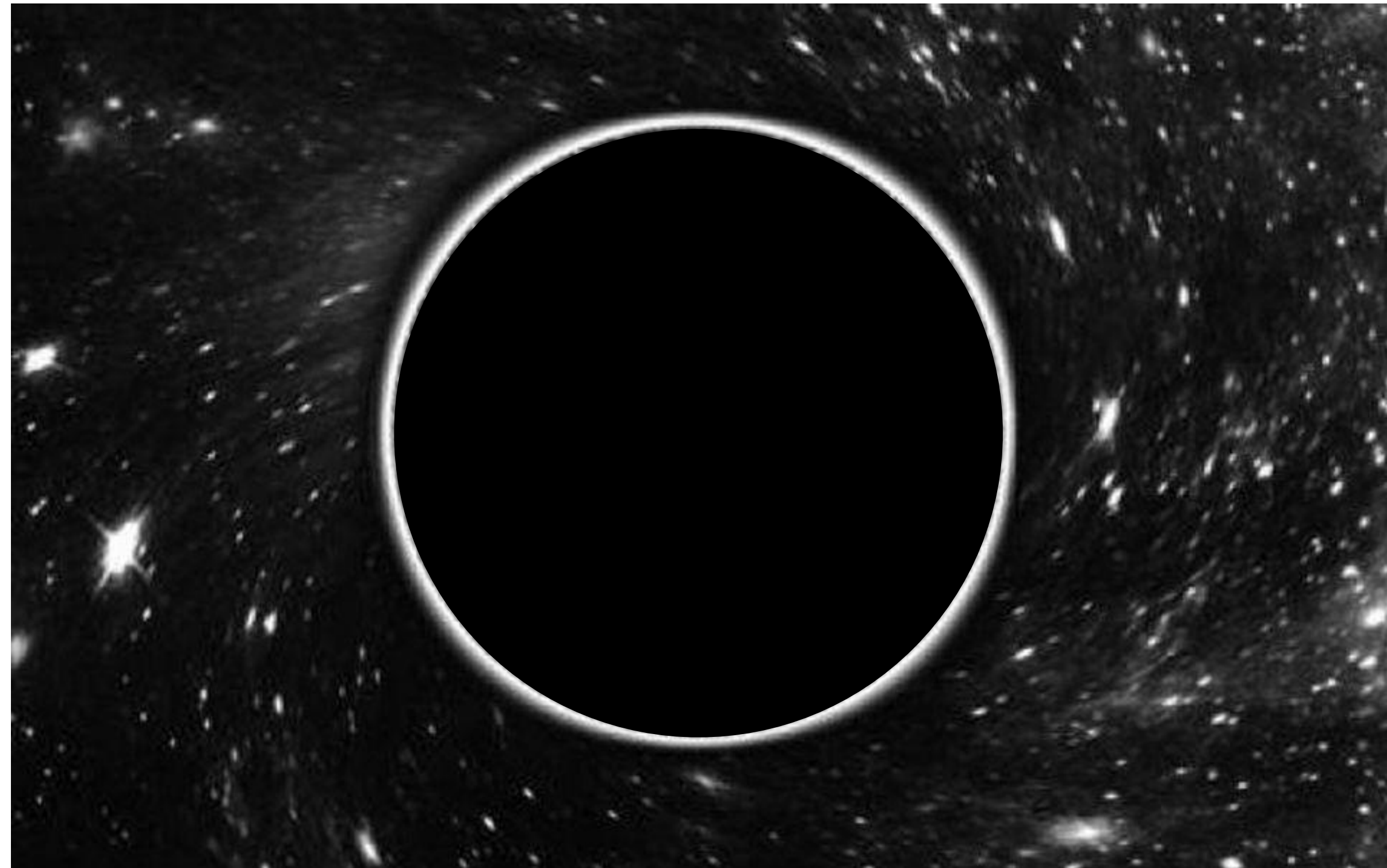


HARVARD

# Quantum Black holes

We learnt from Juan that.....

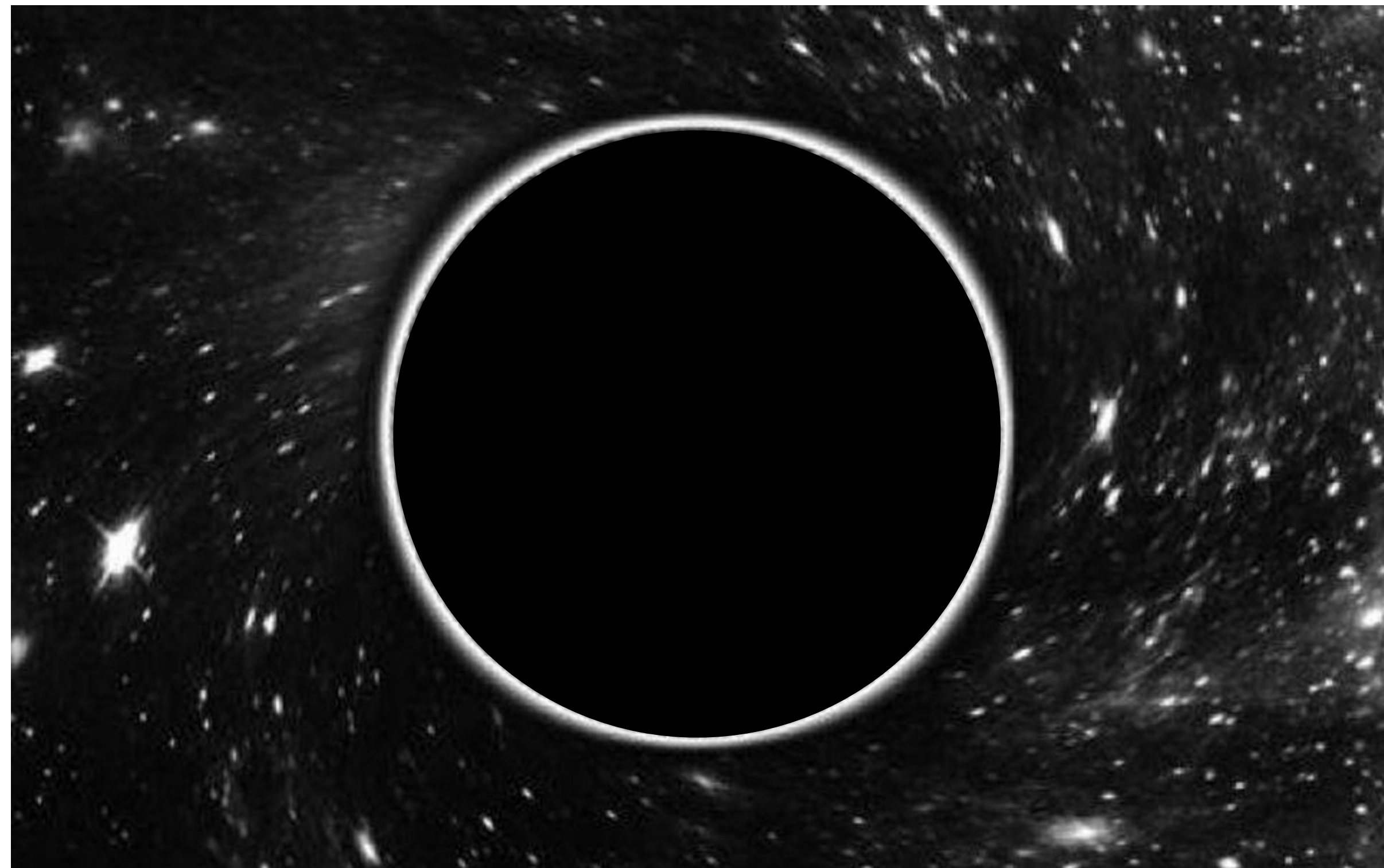
- Black holes have an entropy and a temperature.
- The entropy is proportional to their surface area.



# Quantum Black holes

One more important fact...

- Black holes have an entropy and a temperature.
- The entropy is proportional to their surface area.
- They reach thermal equilibrium at the fastest possible rate!



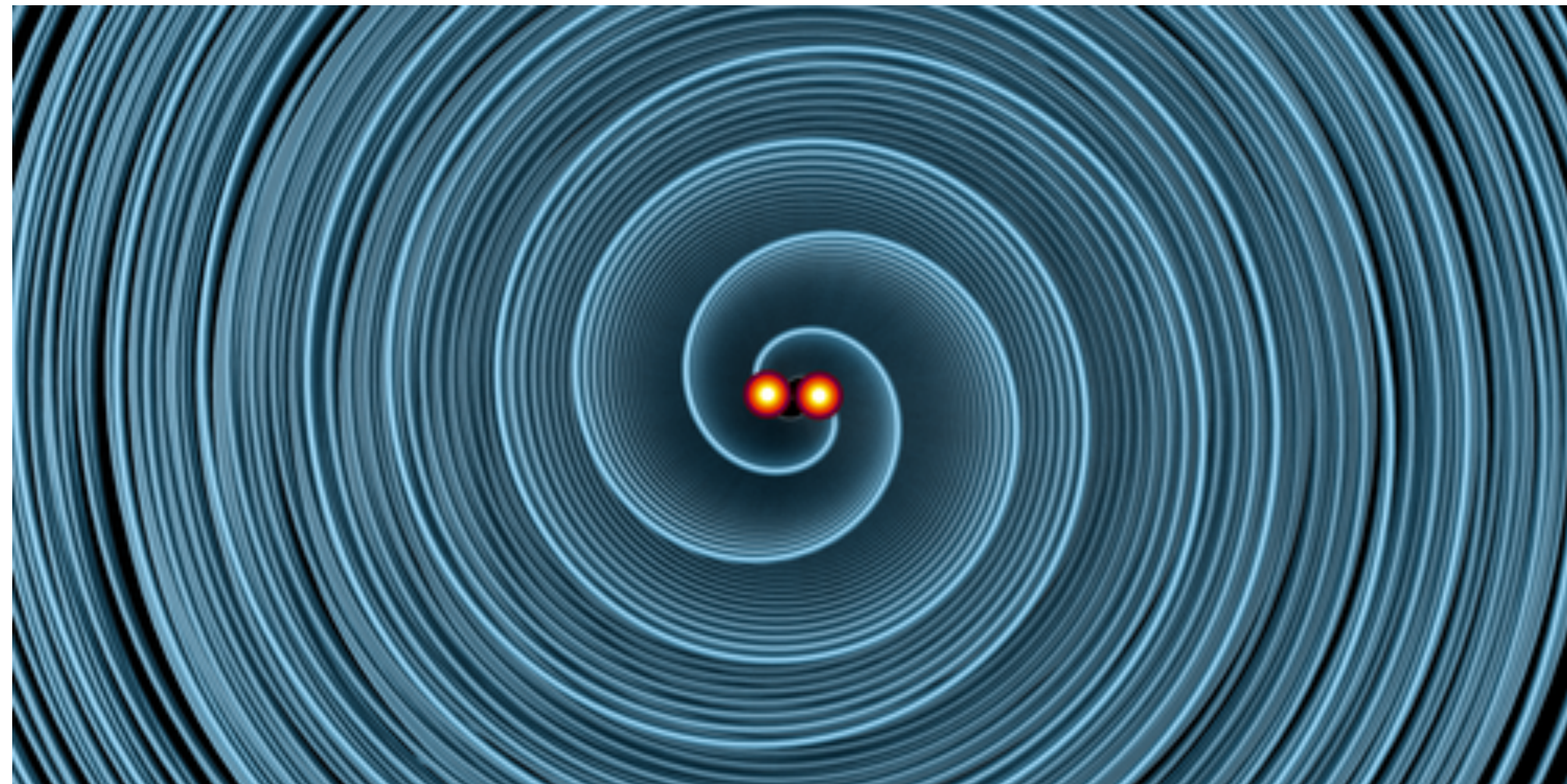
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# Black Holes Obey Information-Emission Limits

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

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

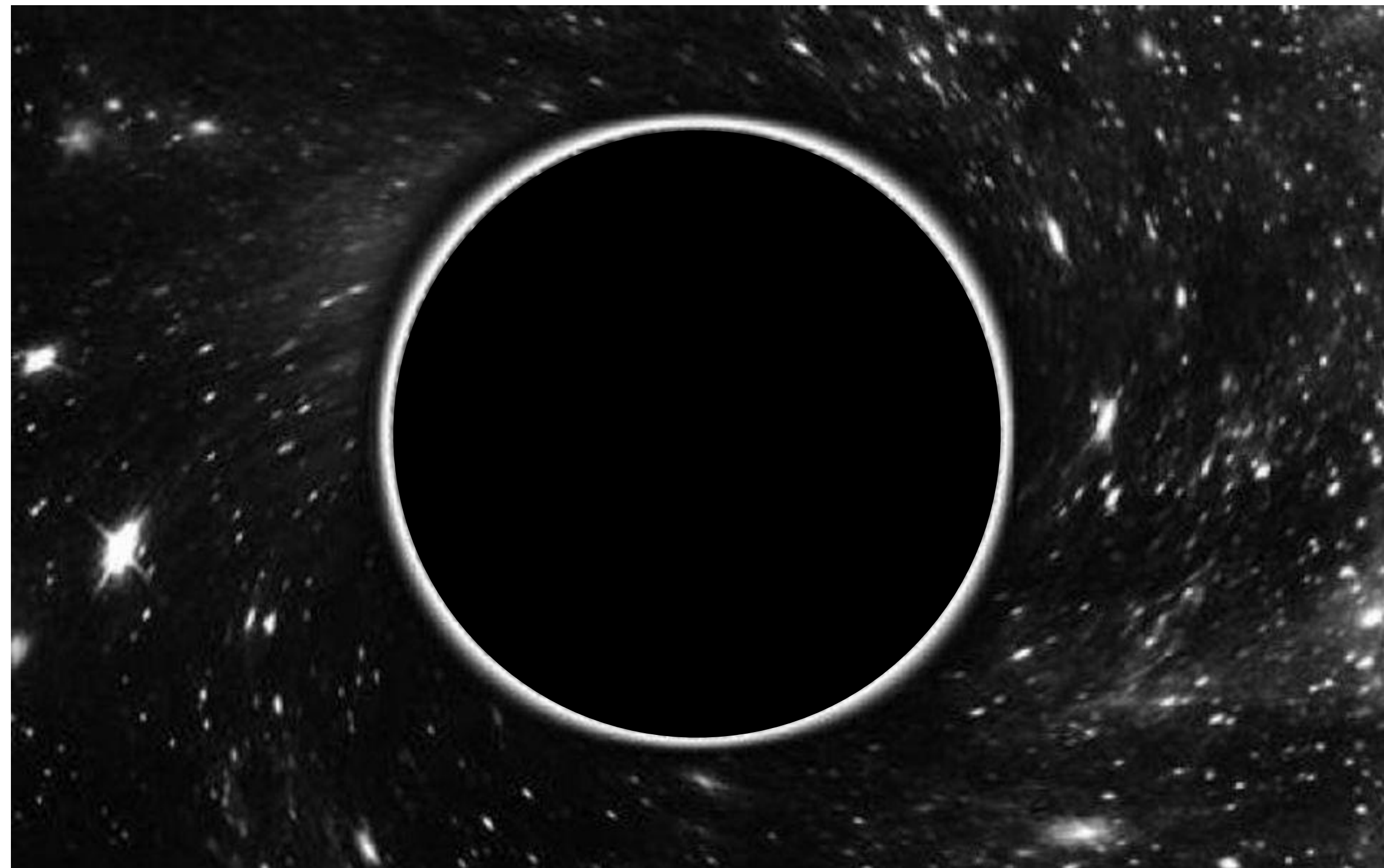
An analysis of the gravitational waves emitted from black hole mergers confirms that black holes are the fastest known information dissipaters.



# Quantum Black holes

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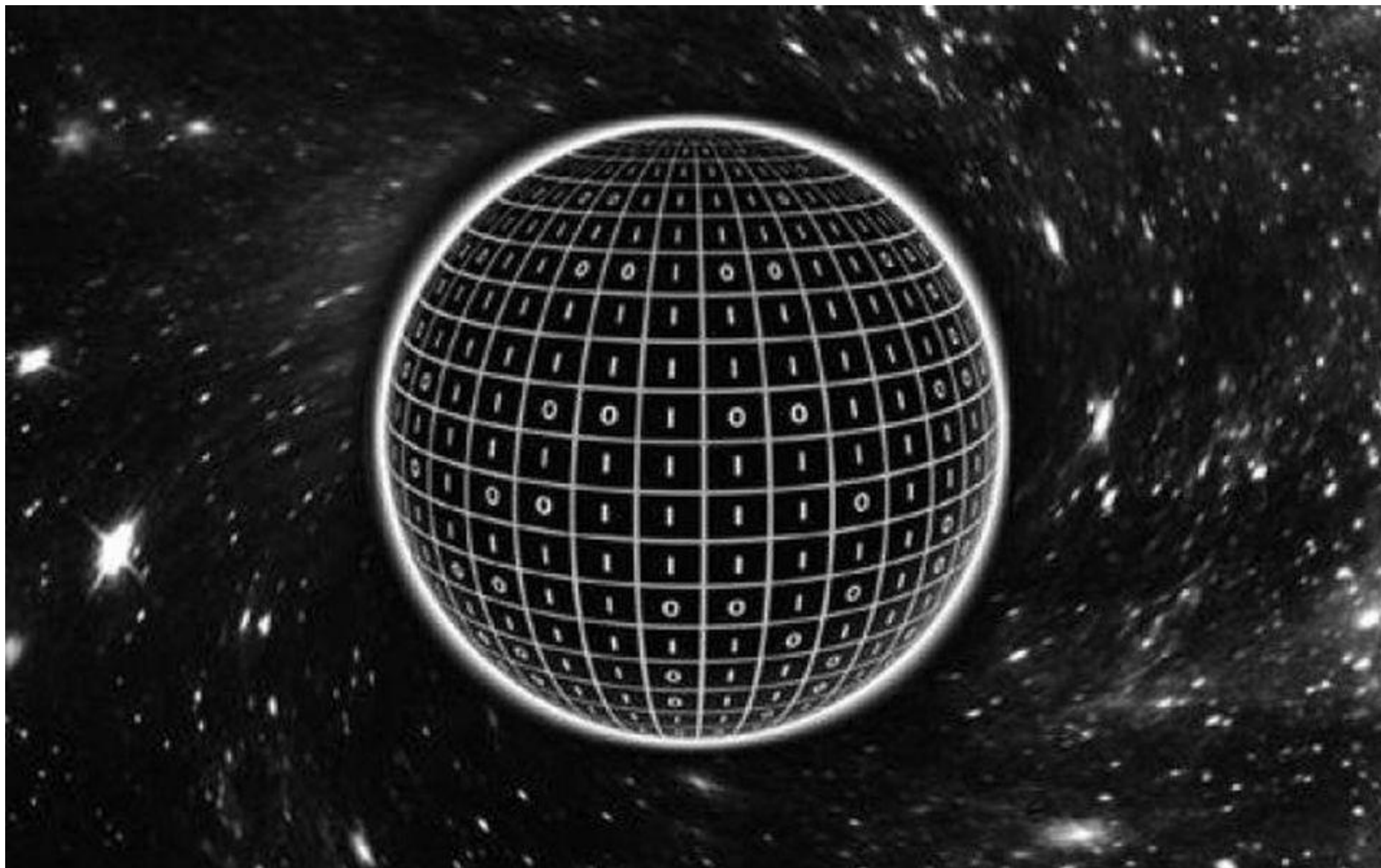
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# Quantum Black holes

A quantum computer simulating a black hole must have:

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- Maximal, long-range quantum entanglement between the qubits



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**Spooky action at a distance!**

natürlicher  
deren Notwendigkeit im Raum  
mus ja zuerst von Dir klar erkannt wurde, einen Bedeutung  
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

amount of validity in the  
recognise clearly as necessary given the framework of  
malism. I cannot seriously believe in it because the theory cannot be rec-  
onciled with the idea that physics should represent a reality in time and  
space, free from spooky actions at a distance. I am, however, not yet  
convinced that it can really be achieved with a continuous field  
... this which so

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

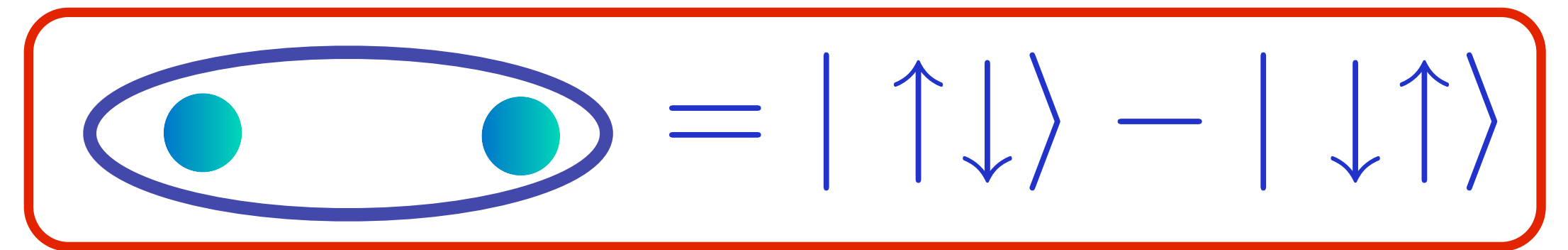
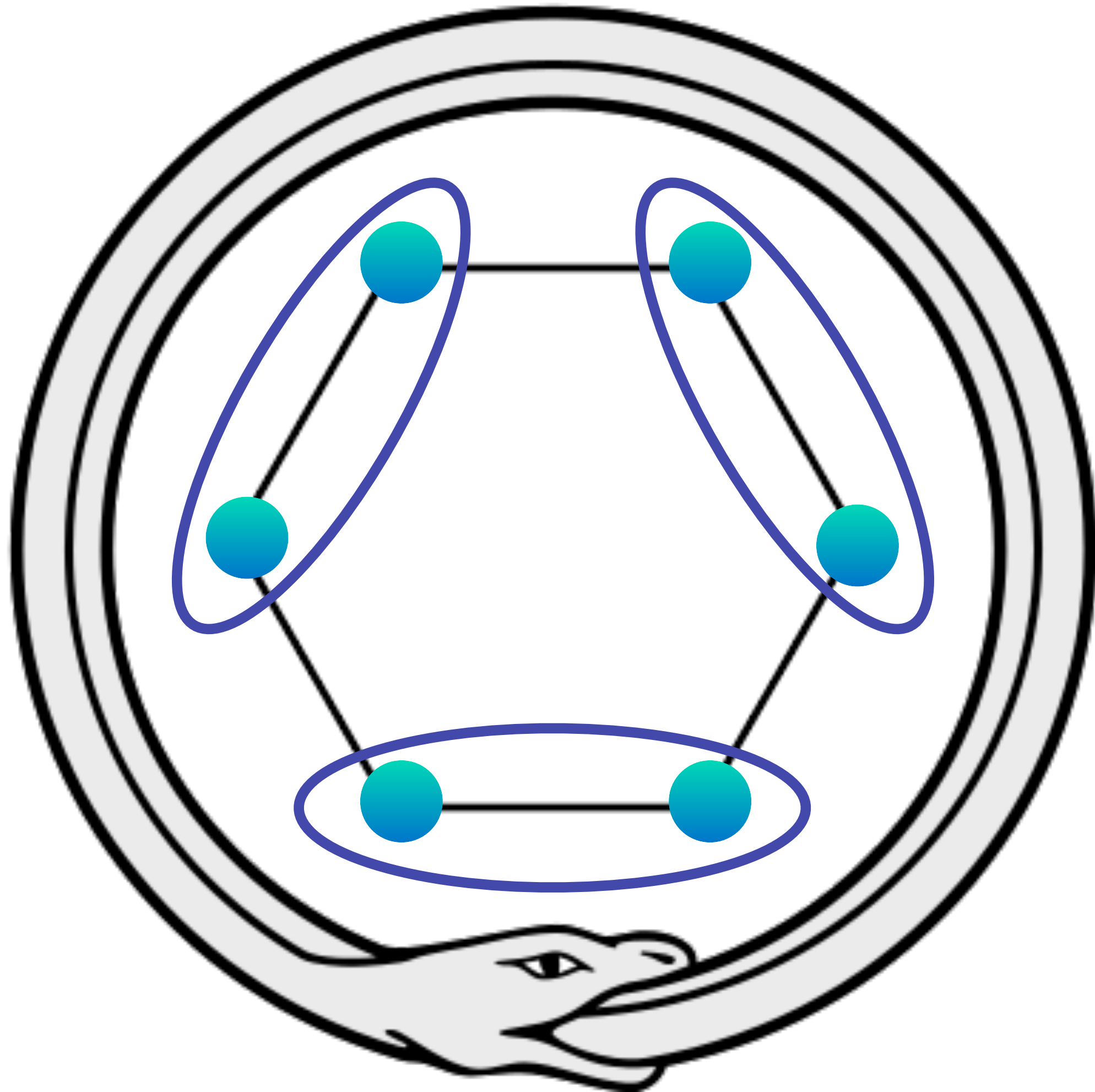
Albert Einstein to Max Born, 3 March 1947



August Kekule, theory of the benzene molecule, 1865

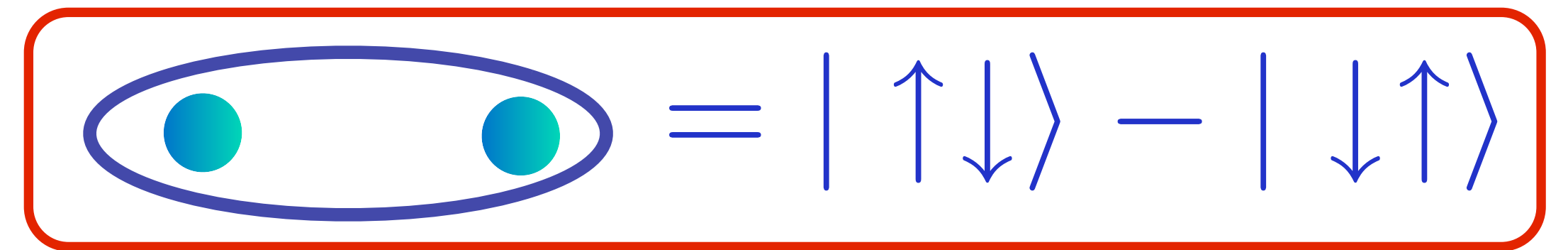
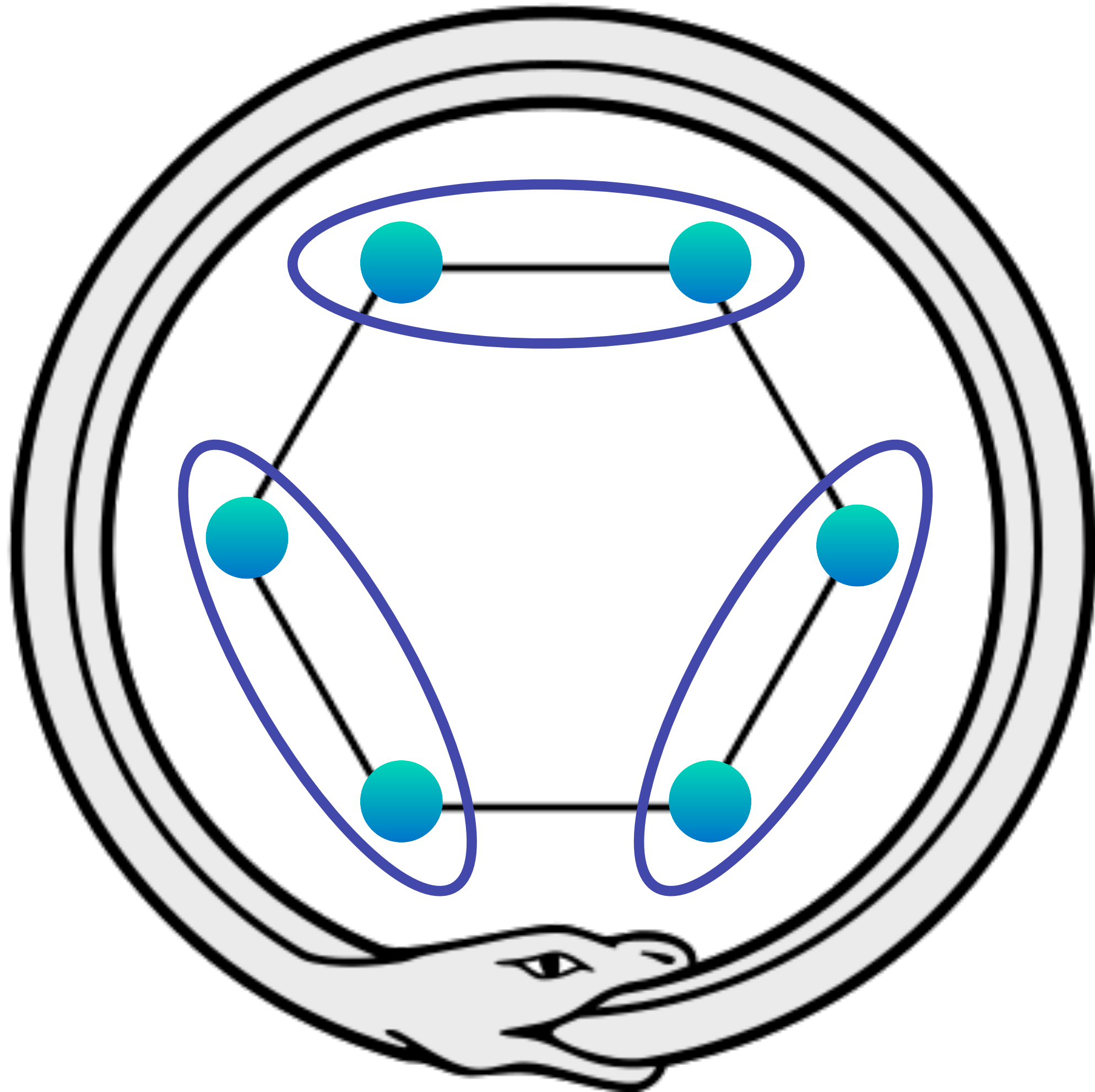
# Kekulé's spooky dream

Here 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\*



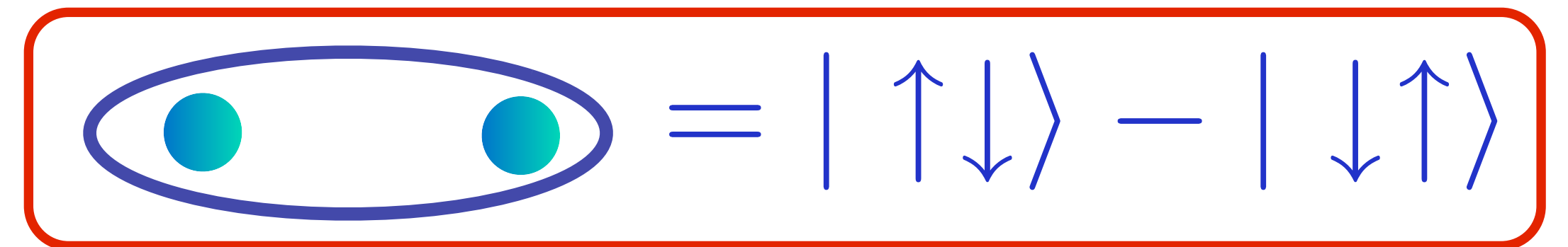
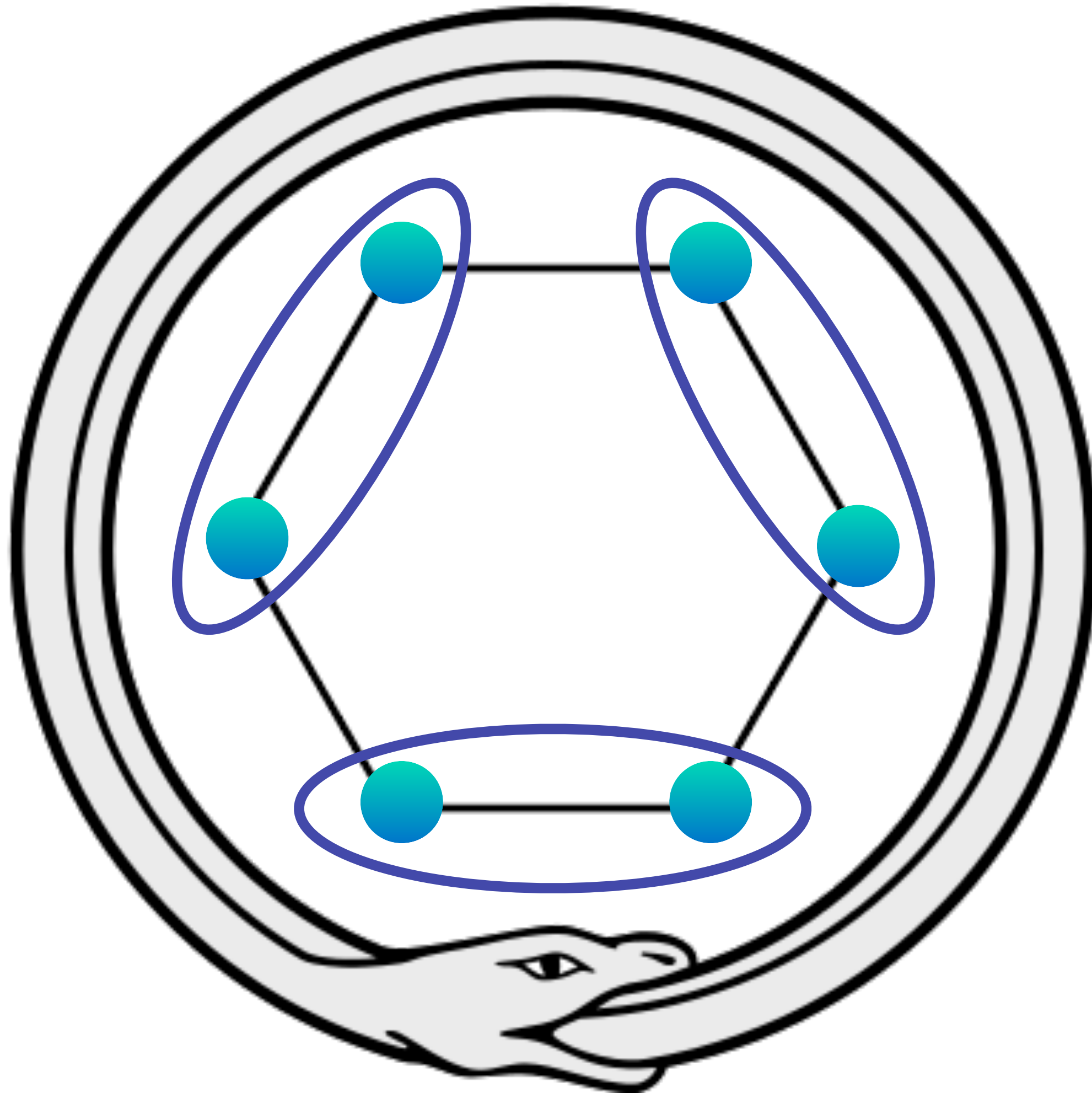
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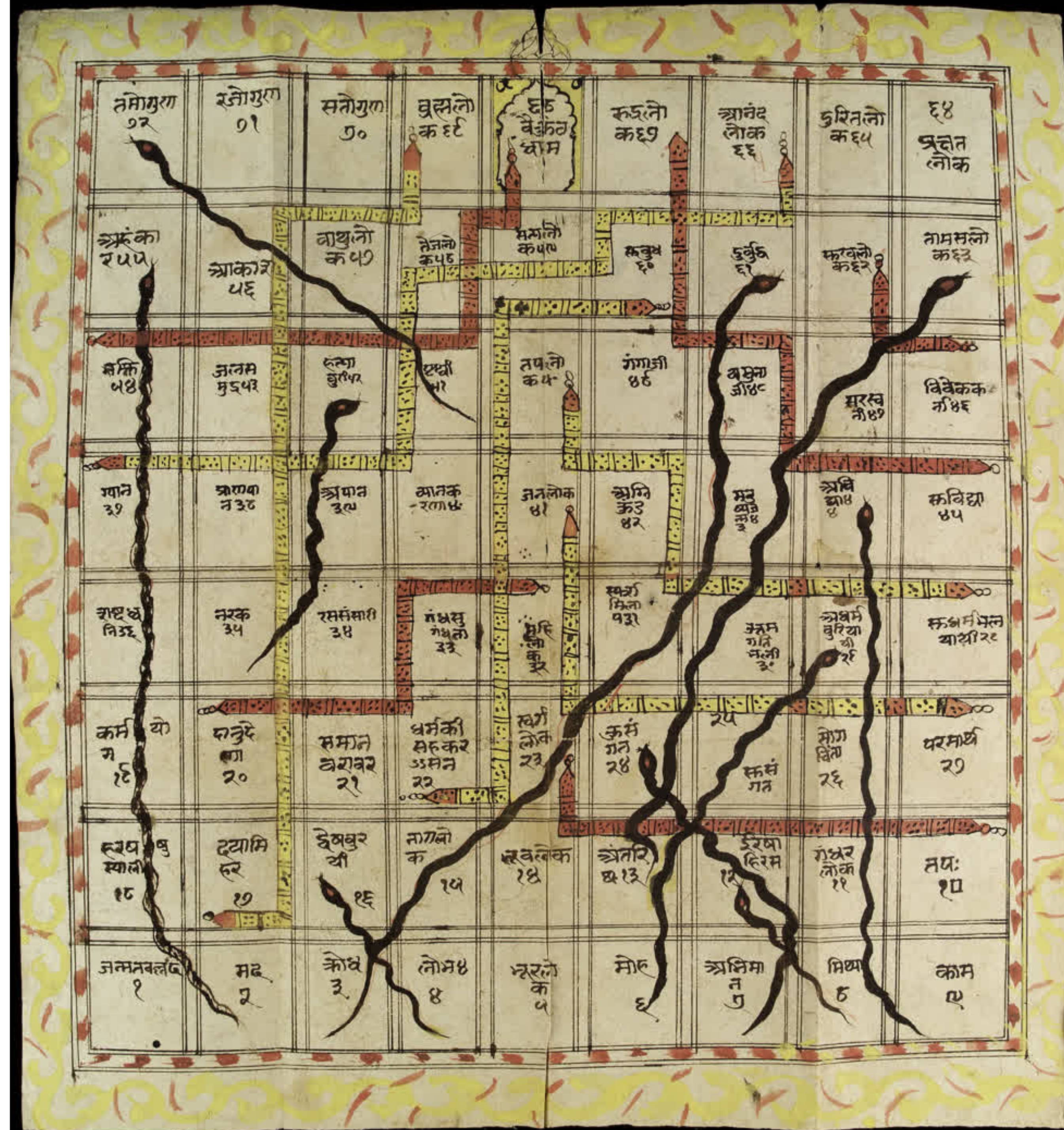
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My  
spooky  
dream\*

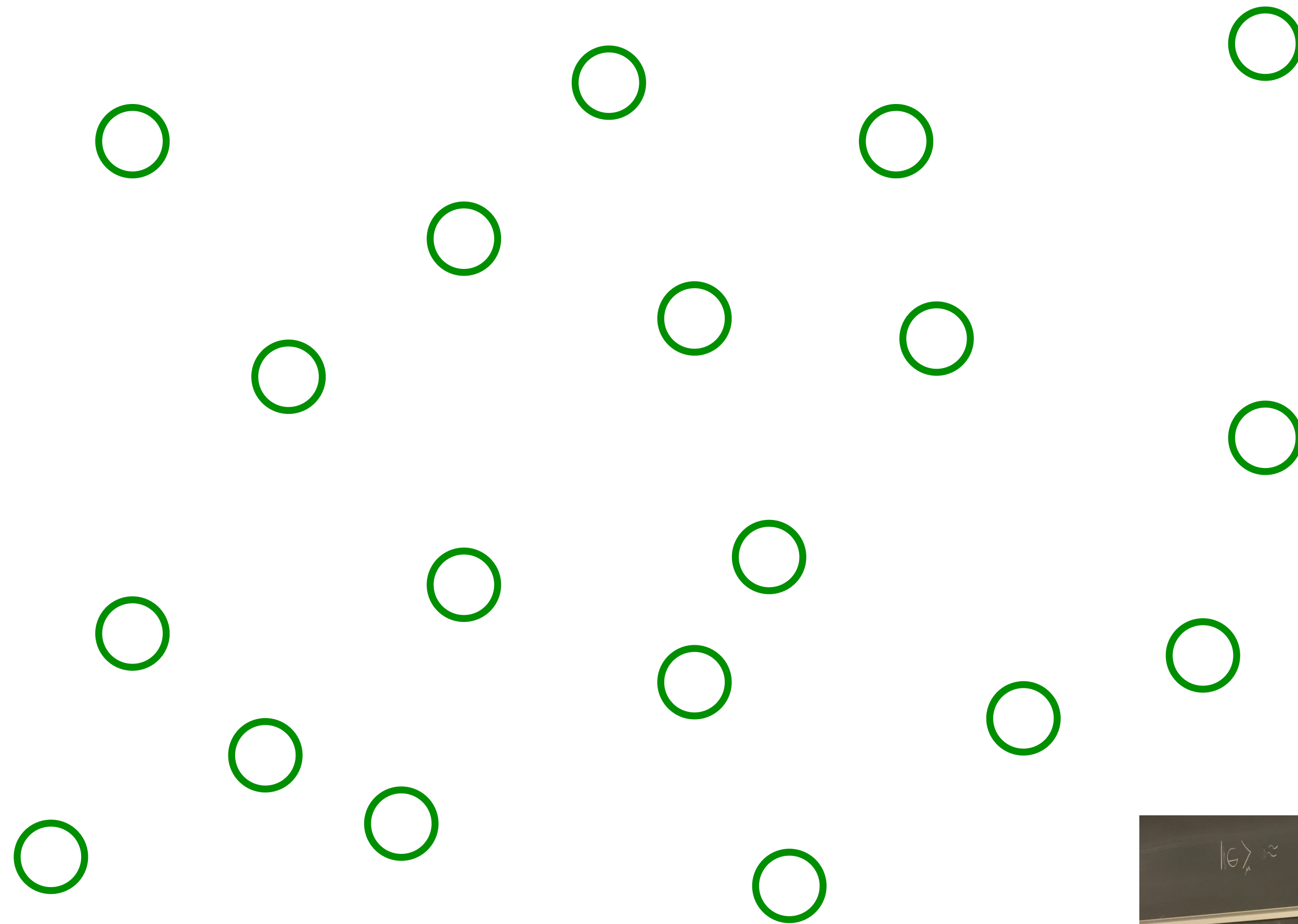
Ancient  
Indian  
game of  
Snakes  
and  
Ladders

\*Not true

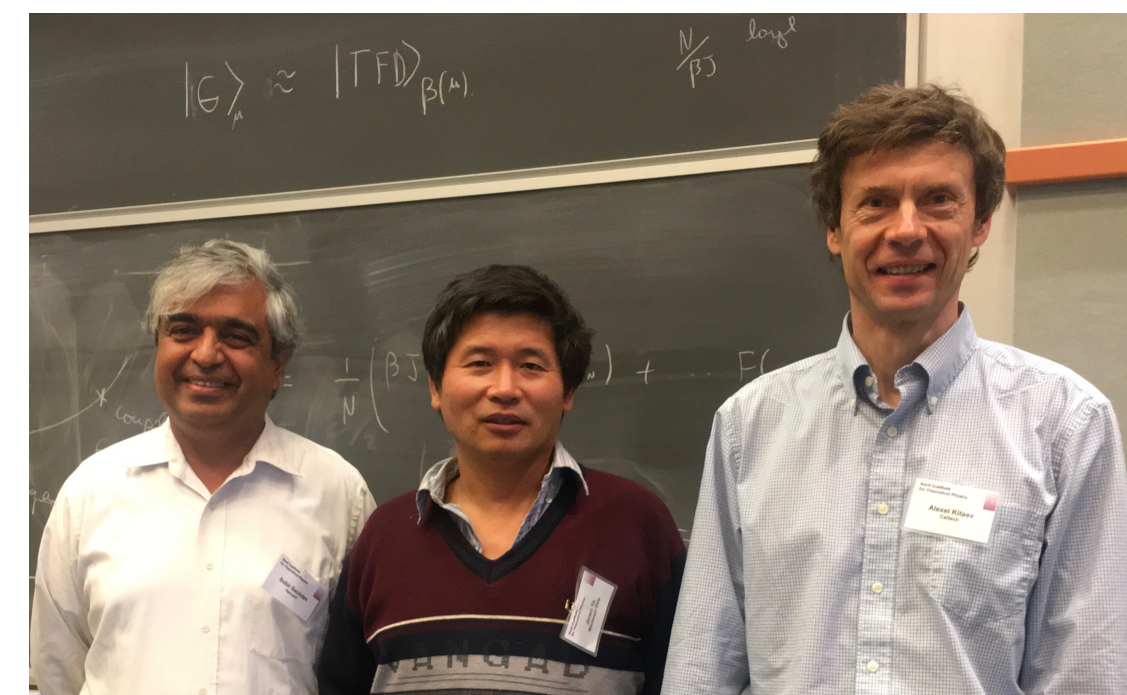


# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

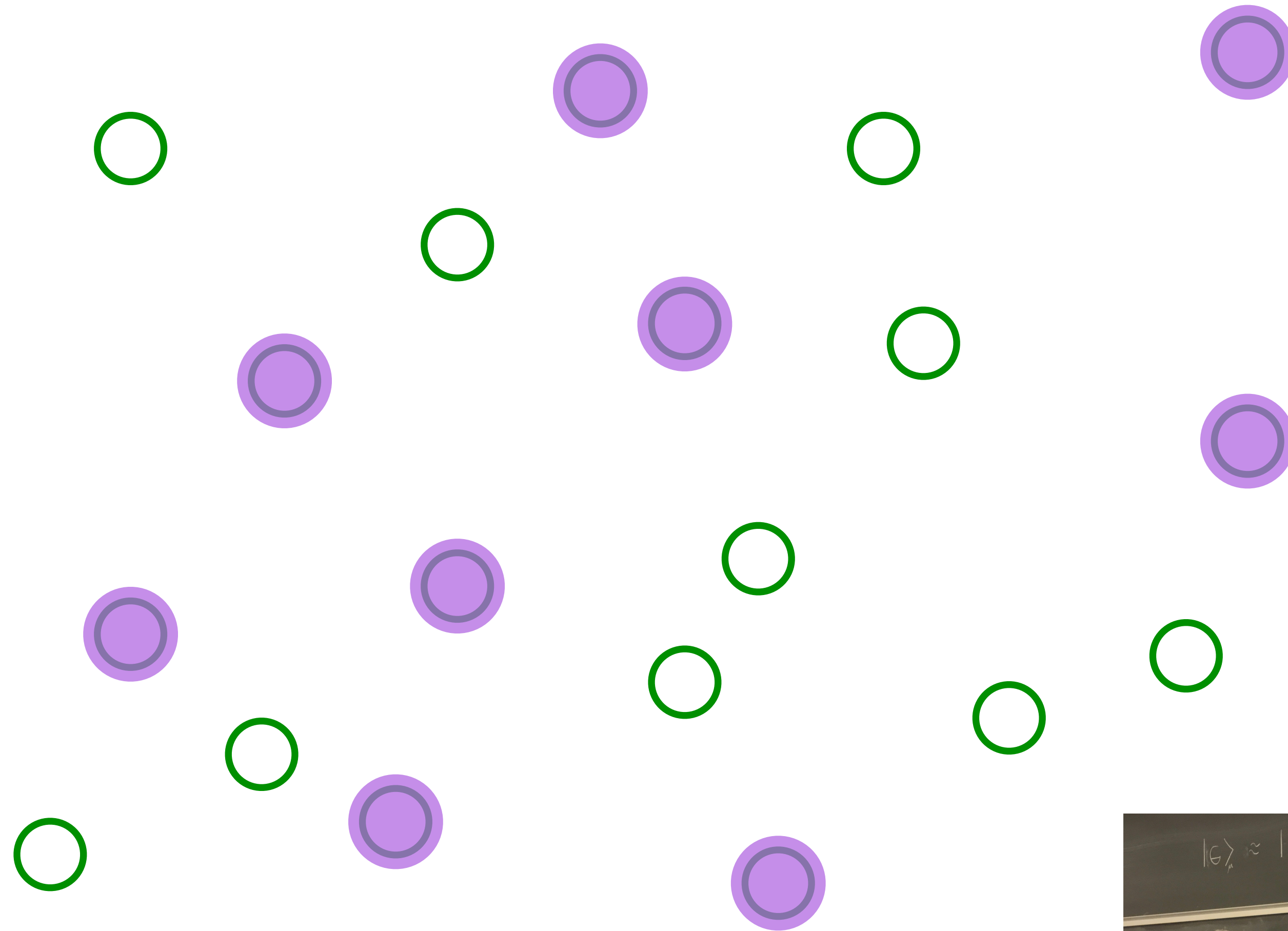


Pick a set of random positions

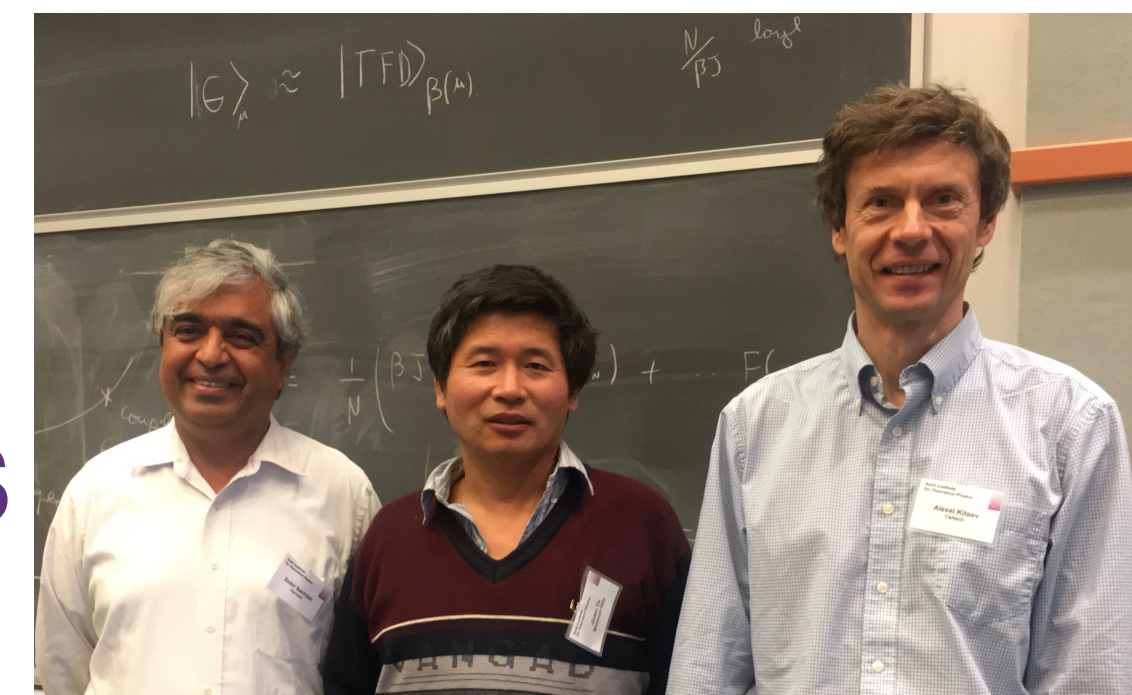


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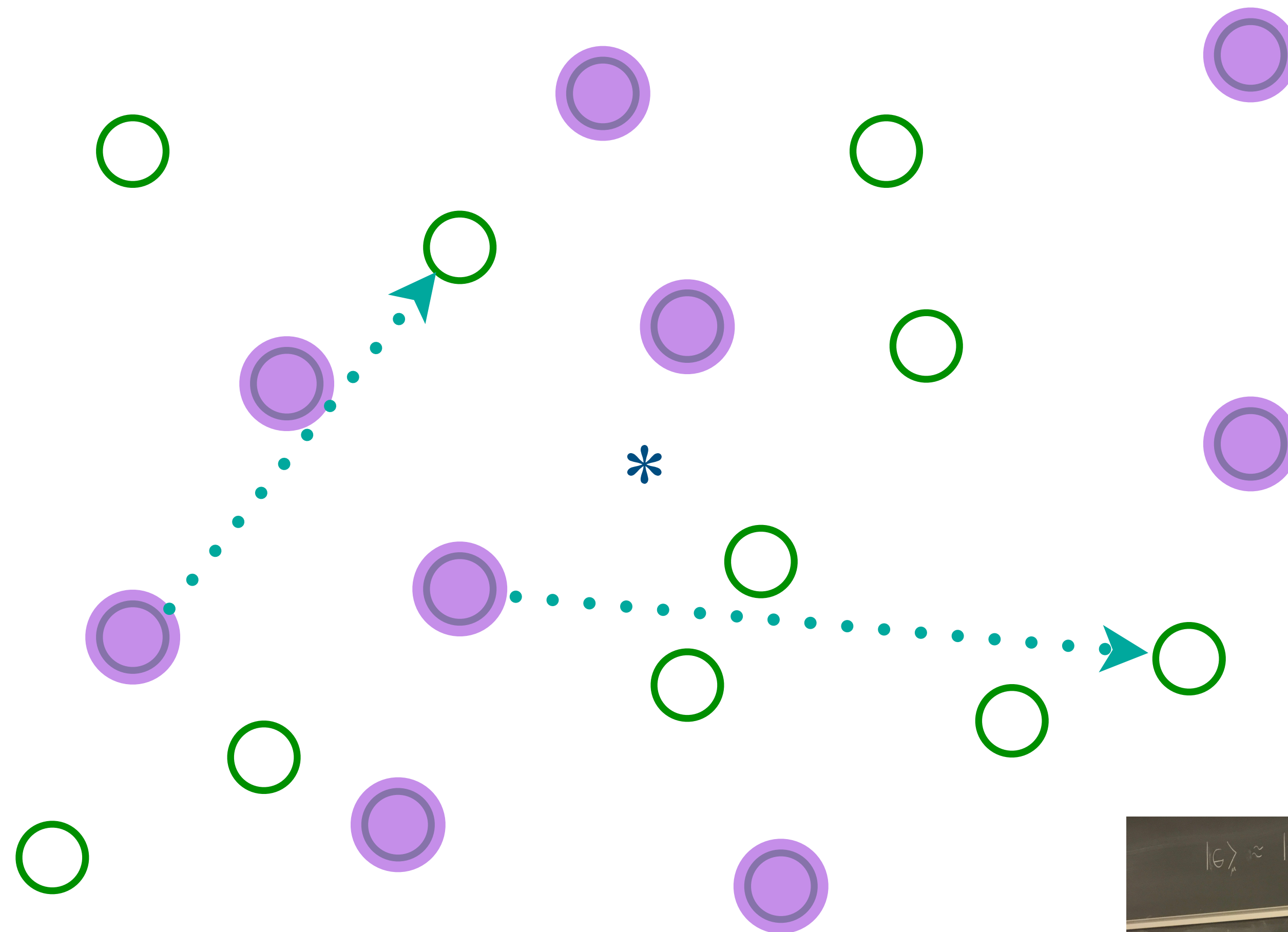


Place electrons randomly on some sites

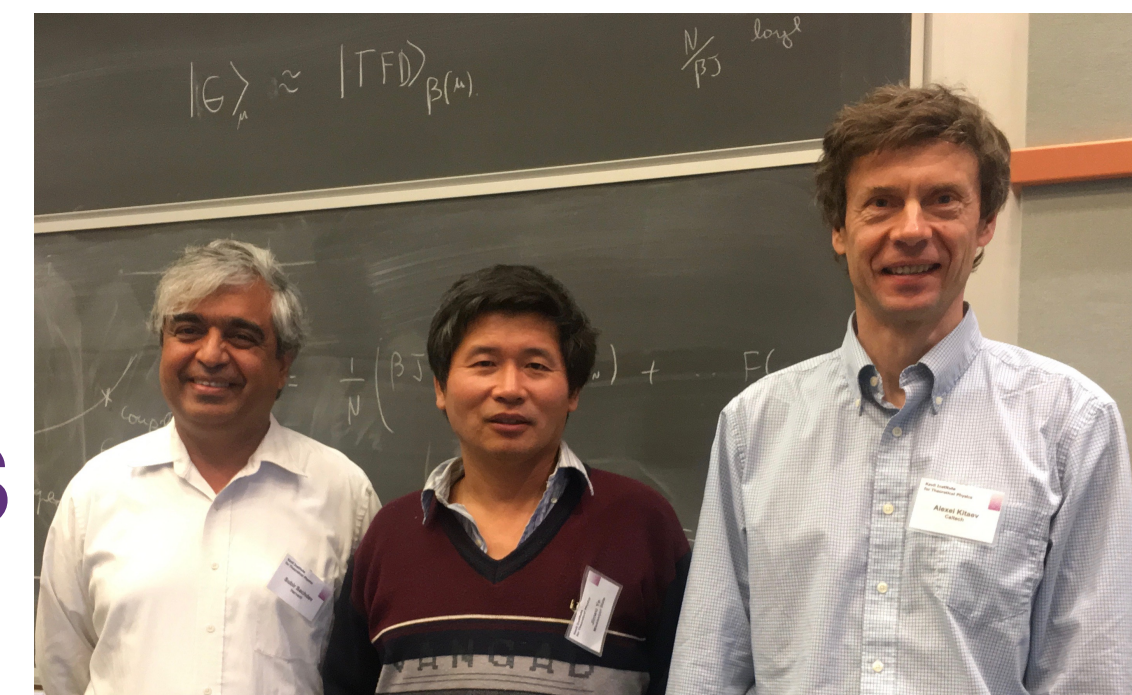


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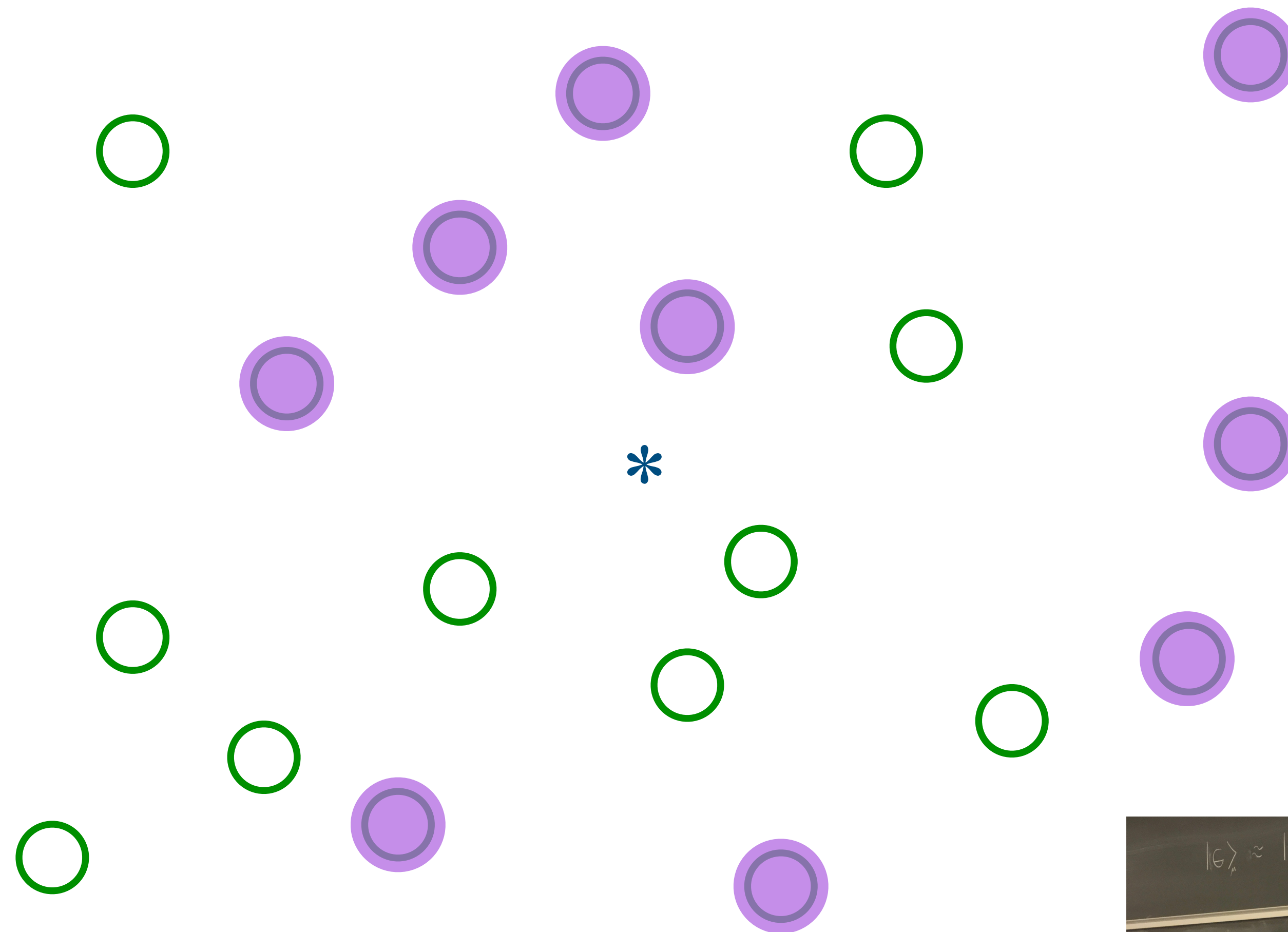


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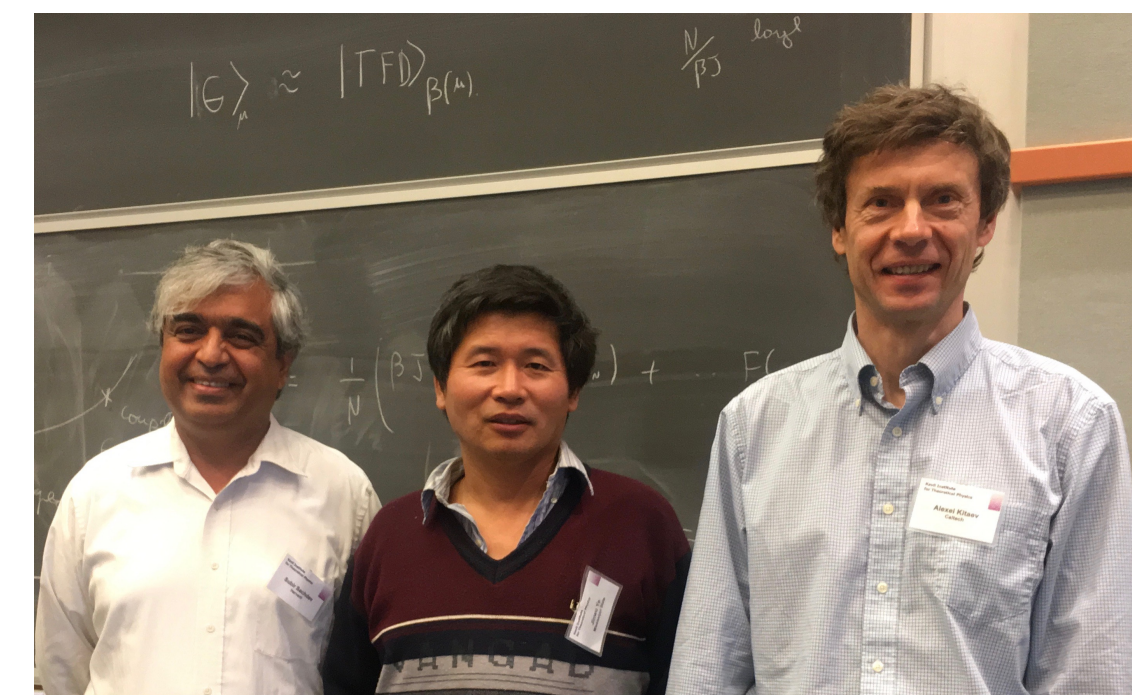


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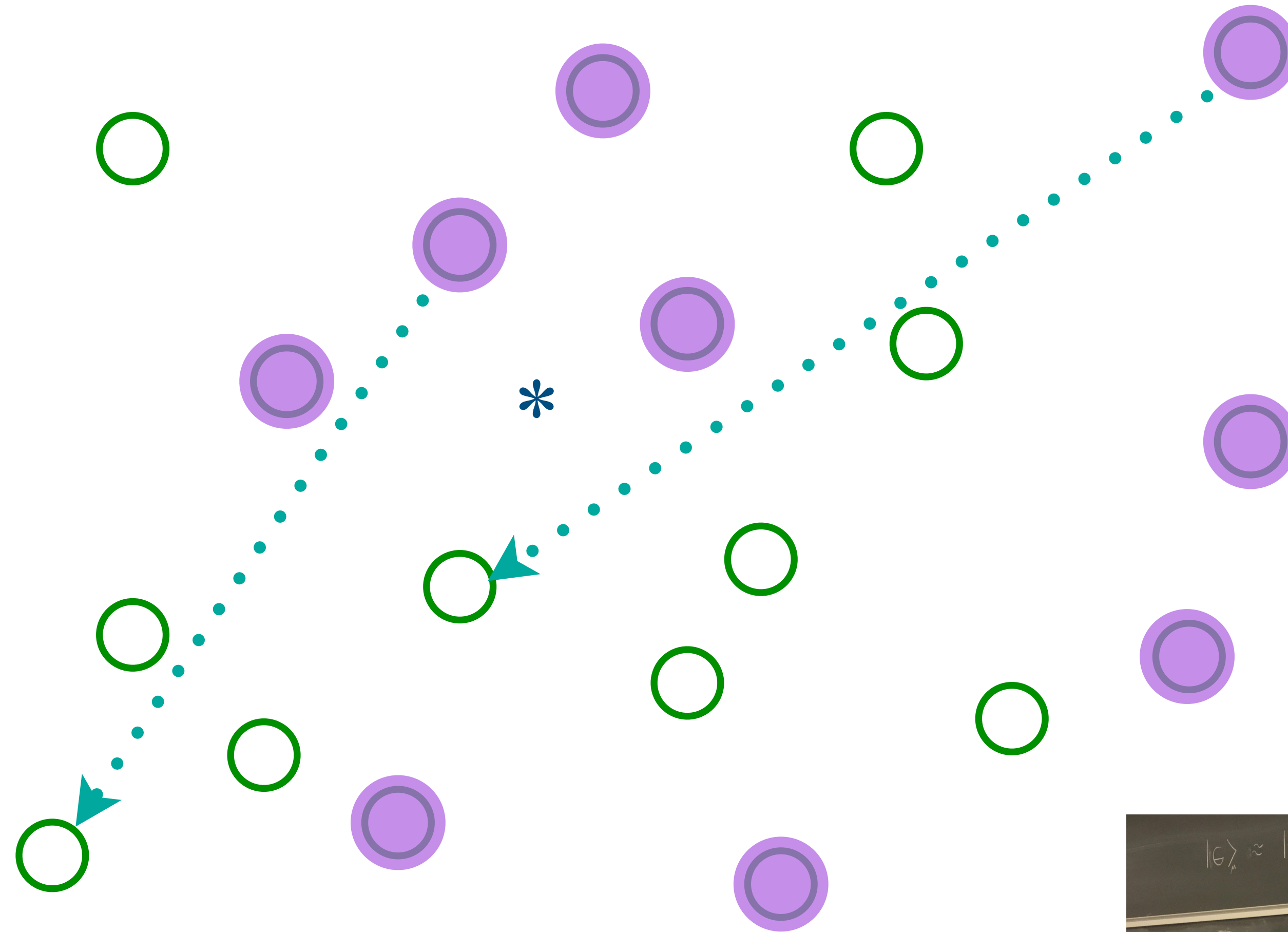


Entangle electrons pairwise randomly

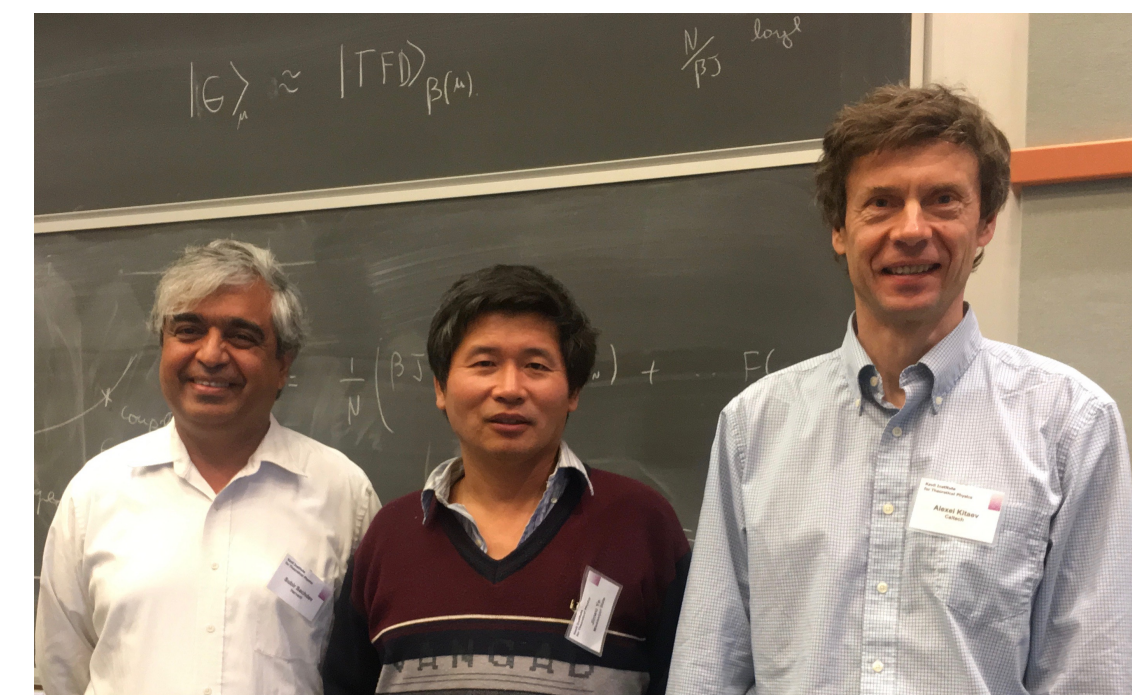


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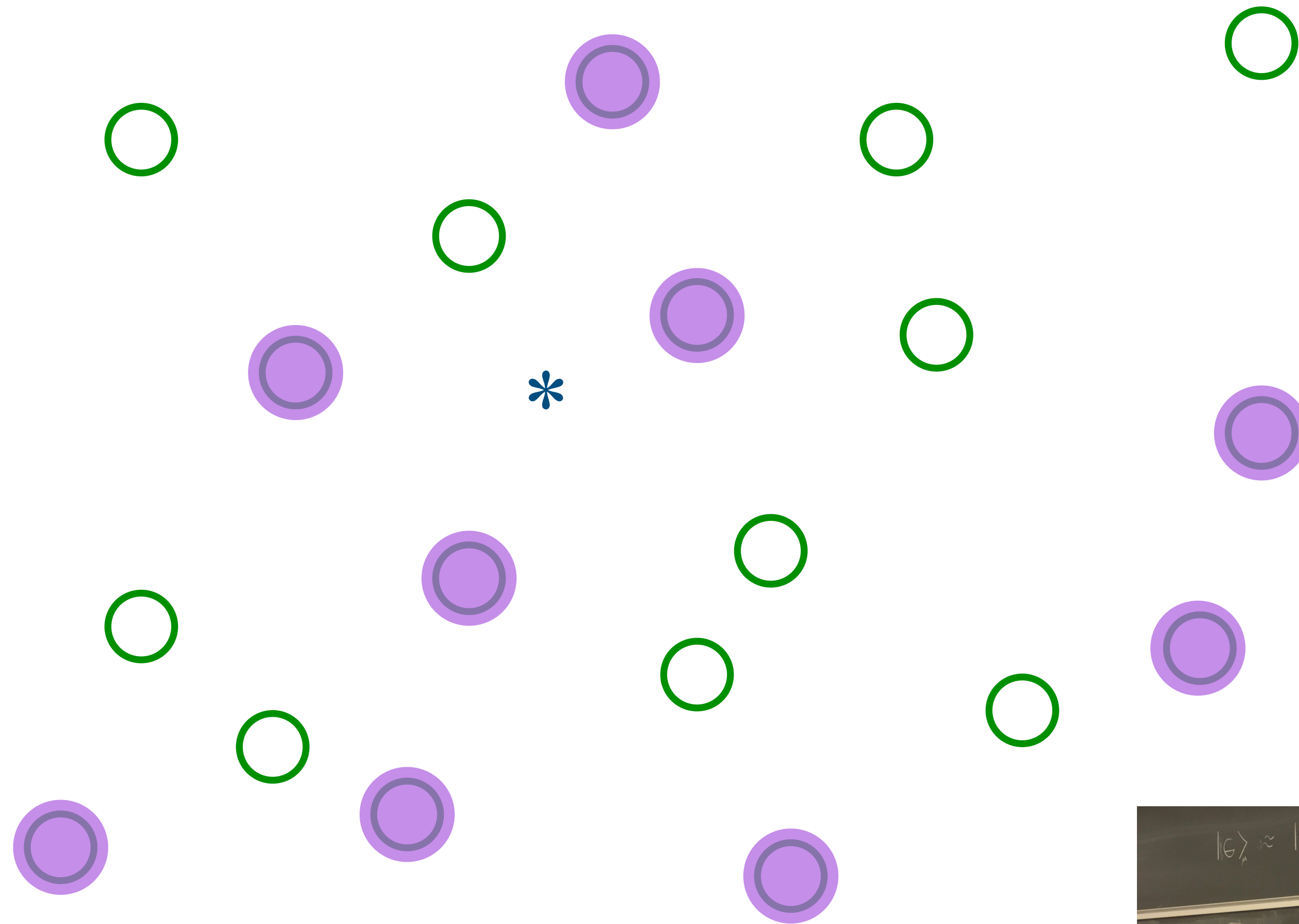


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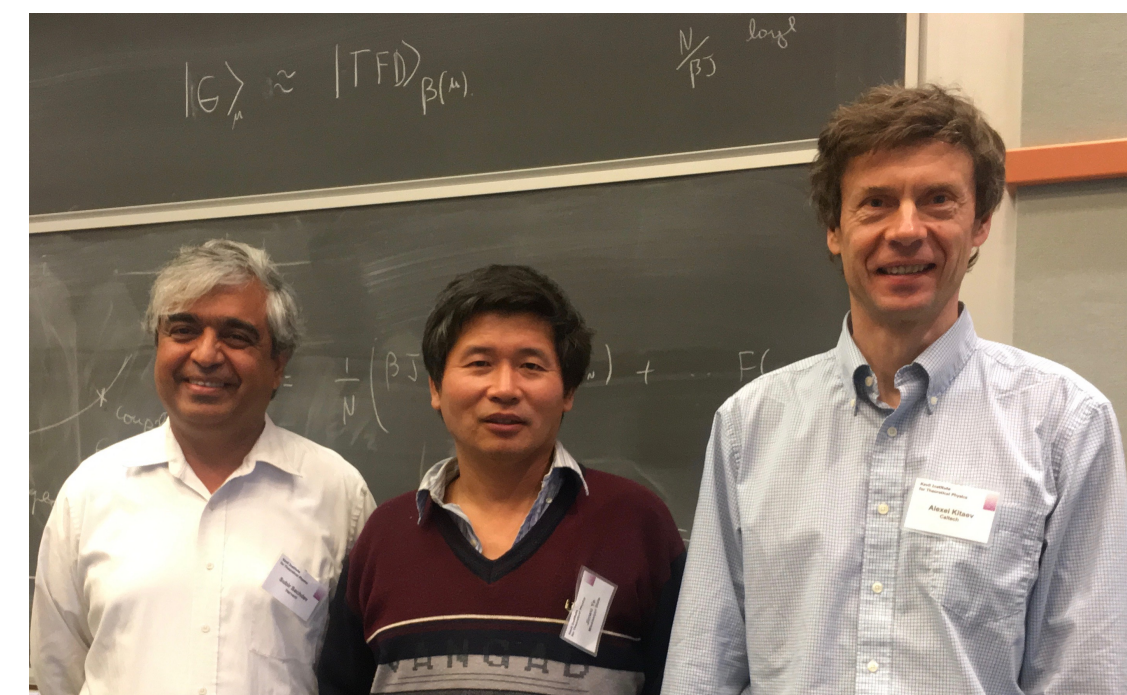


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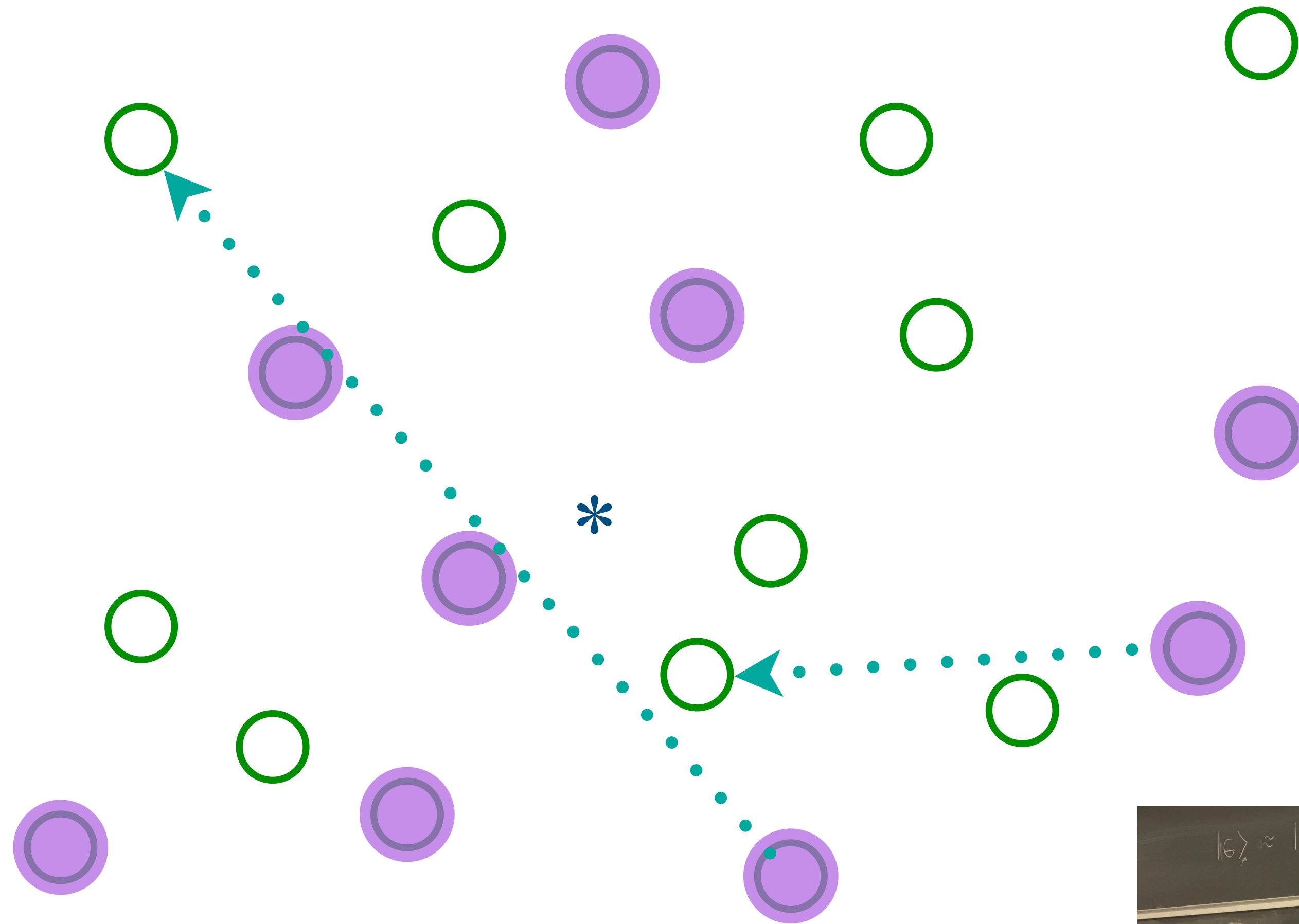


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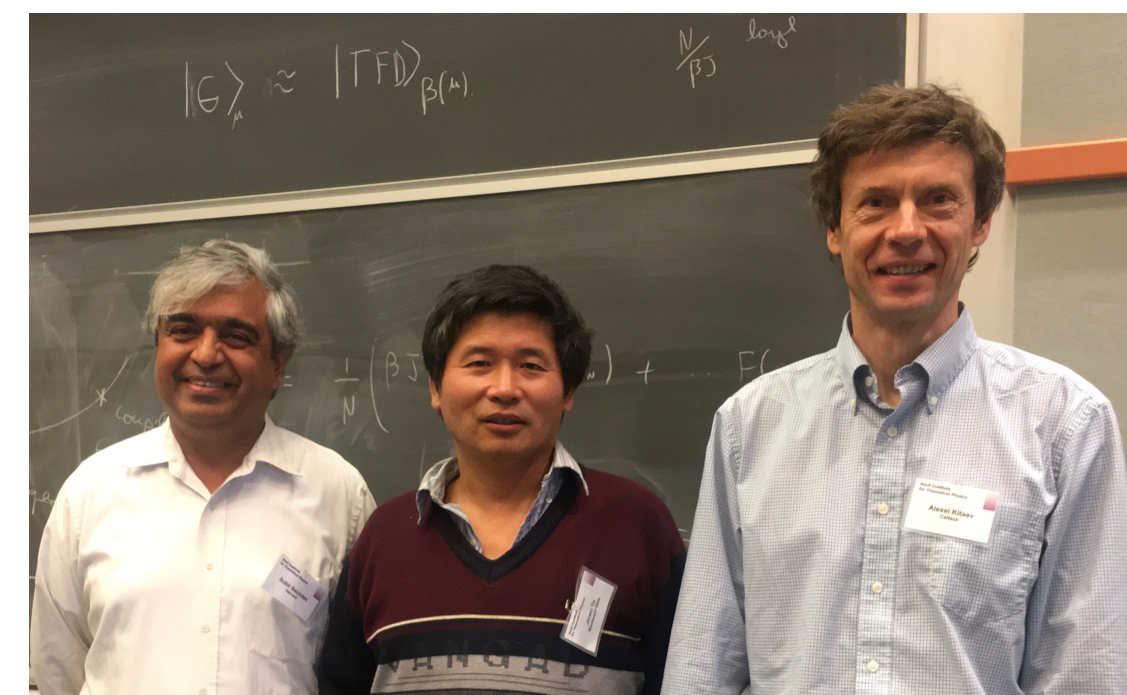


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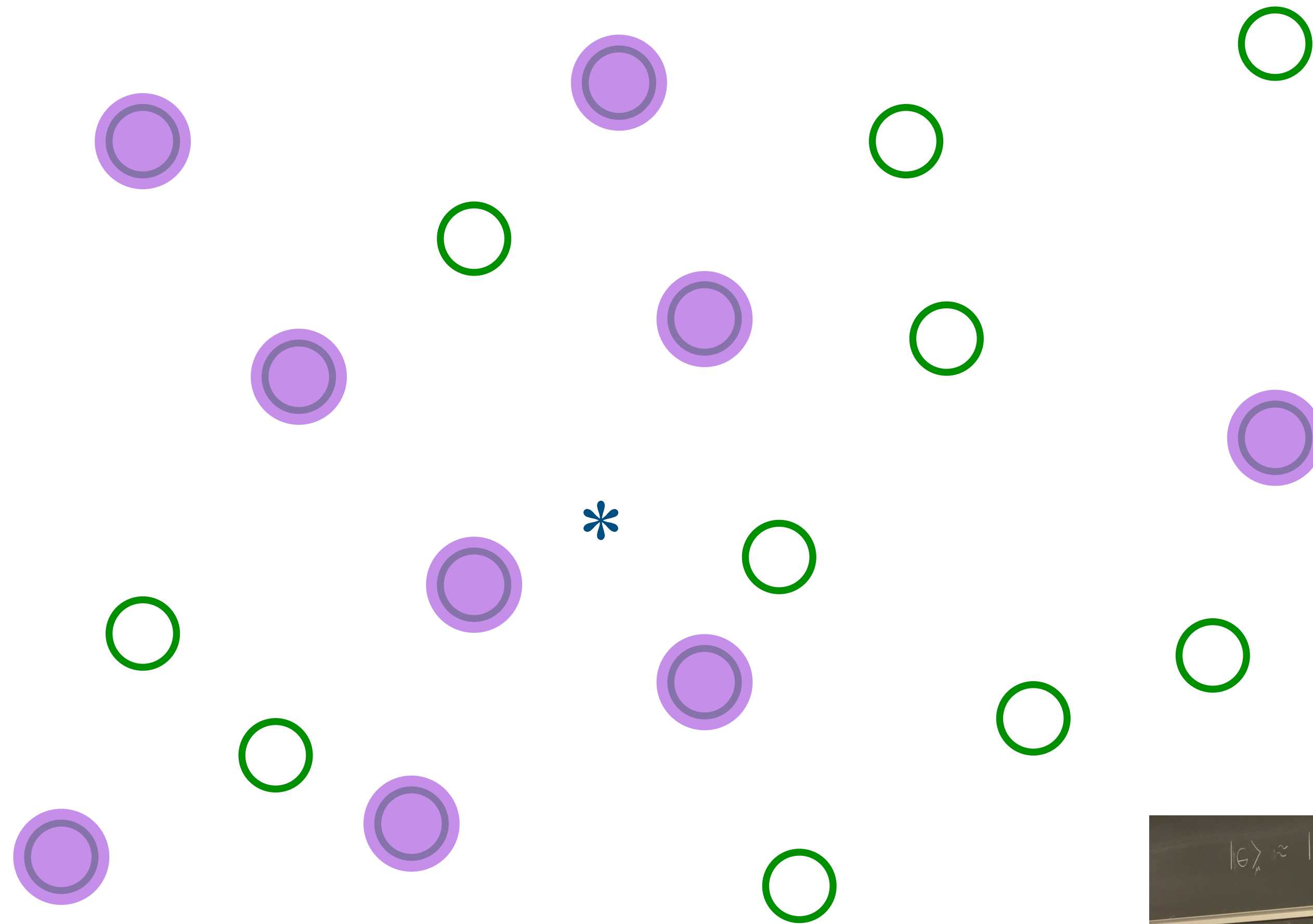


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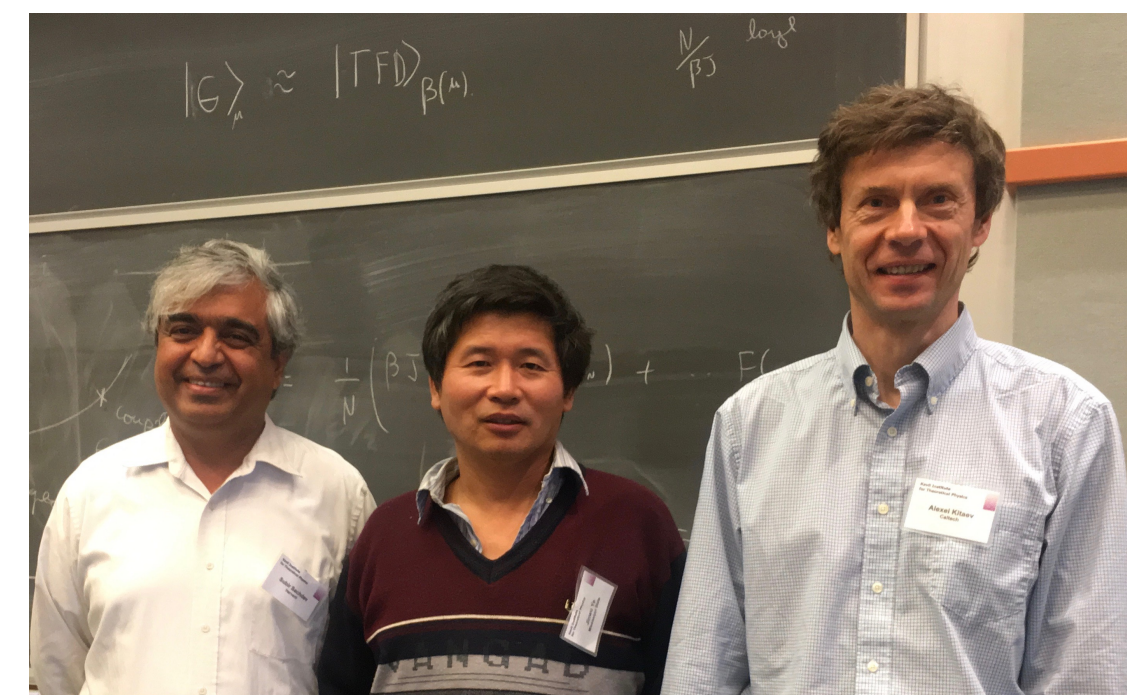


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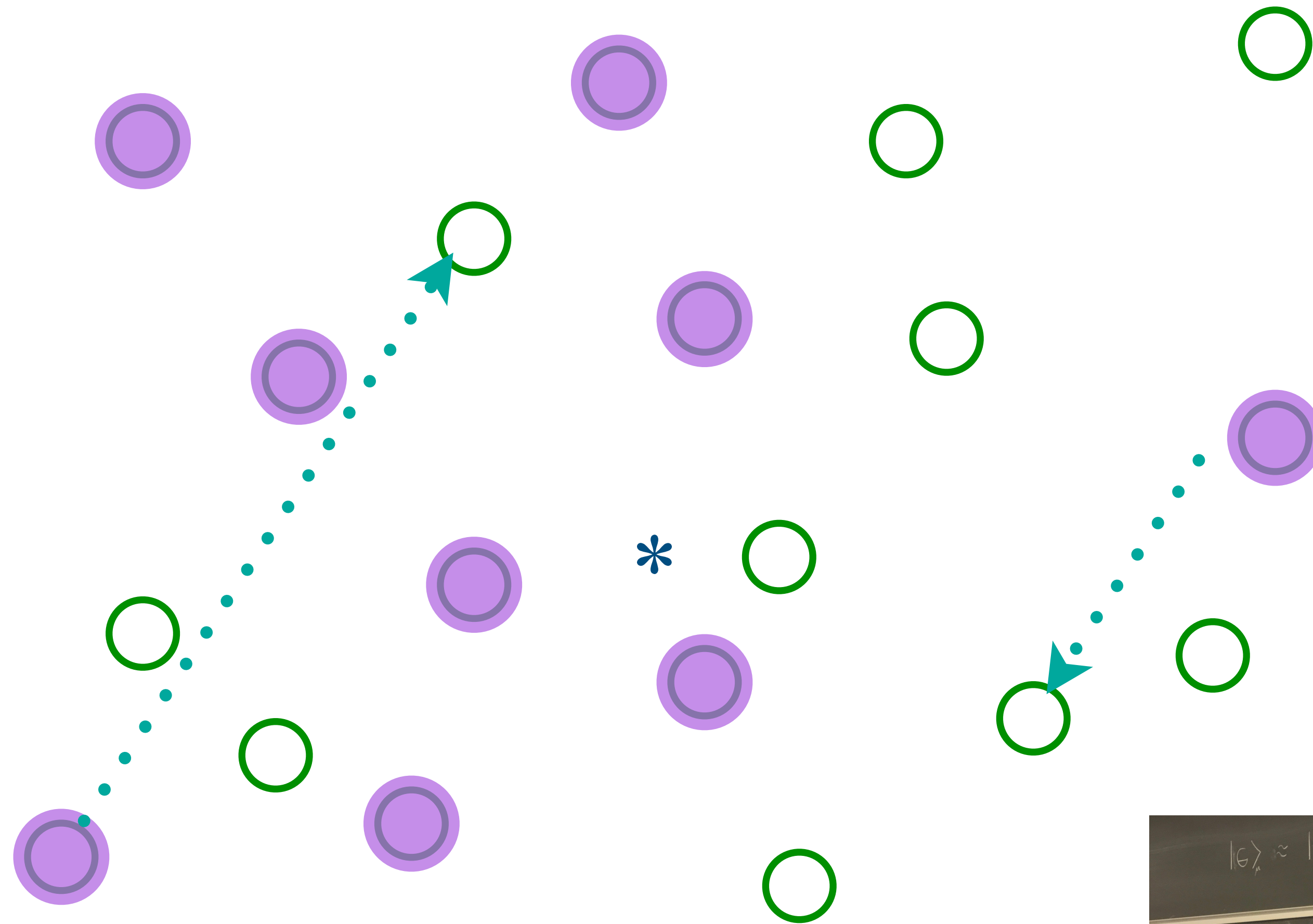


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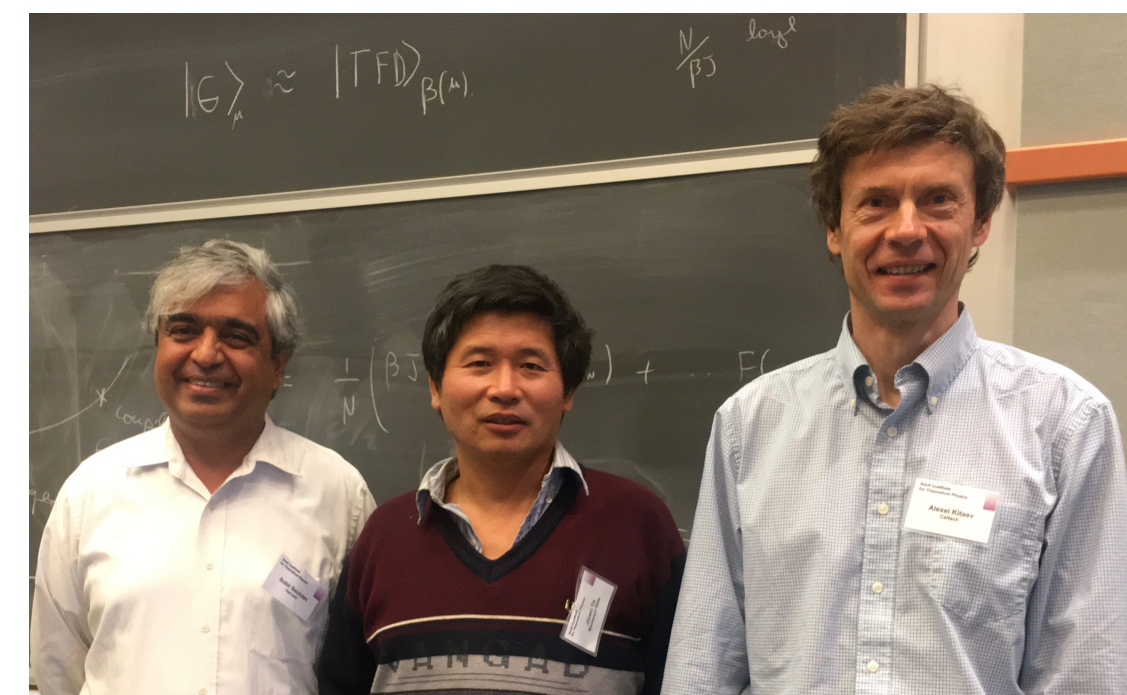


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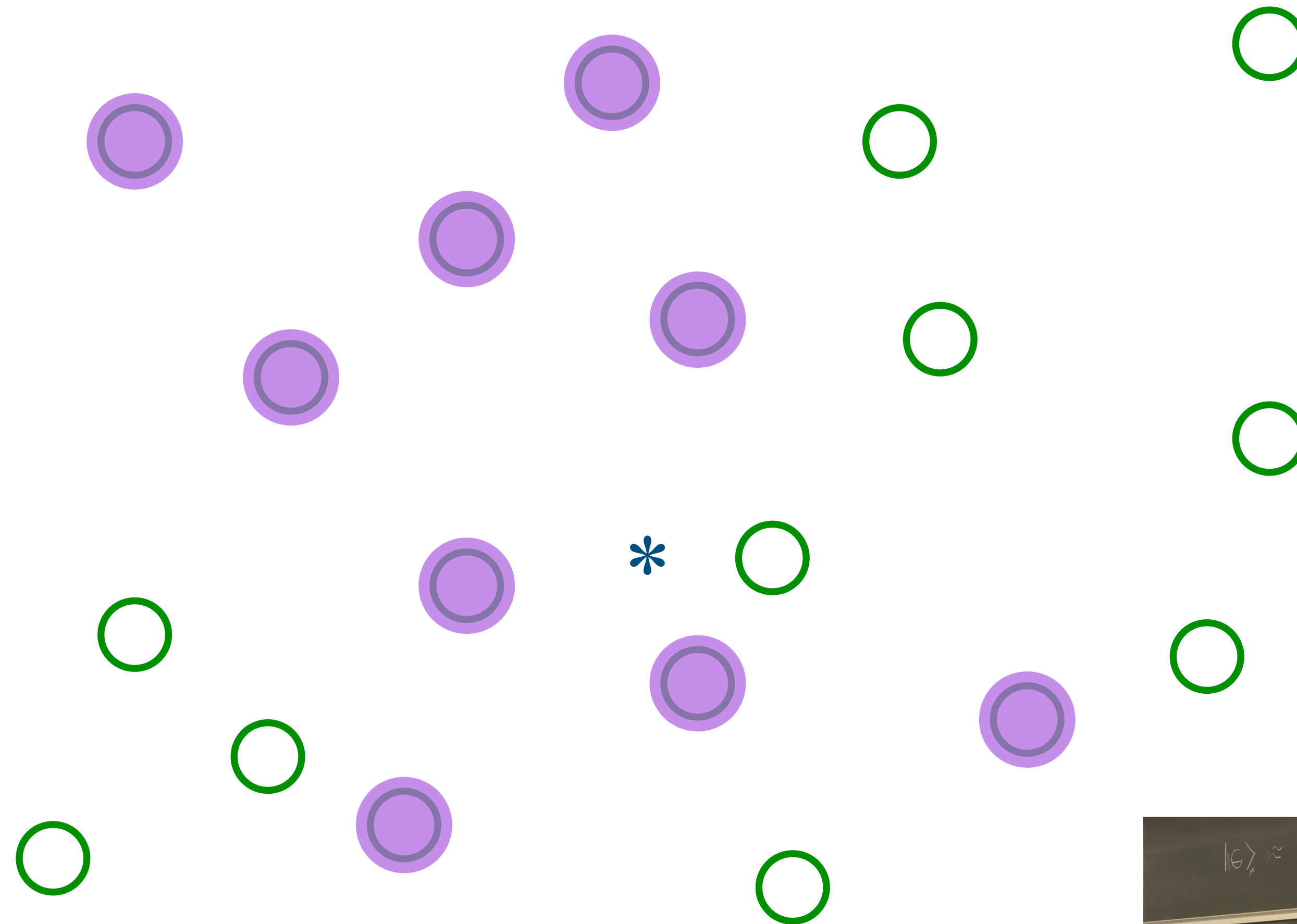


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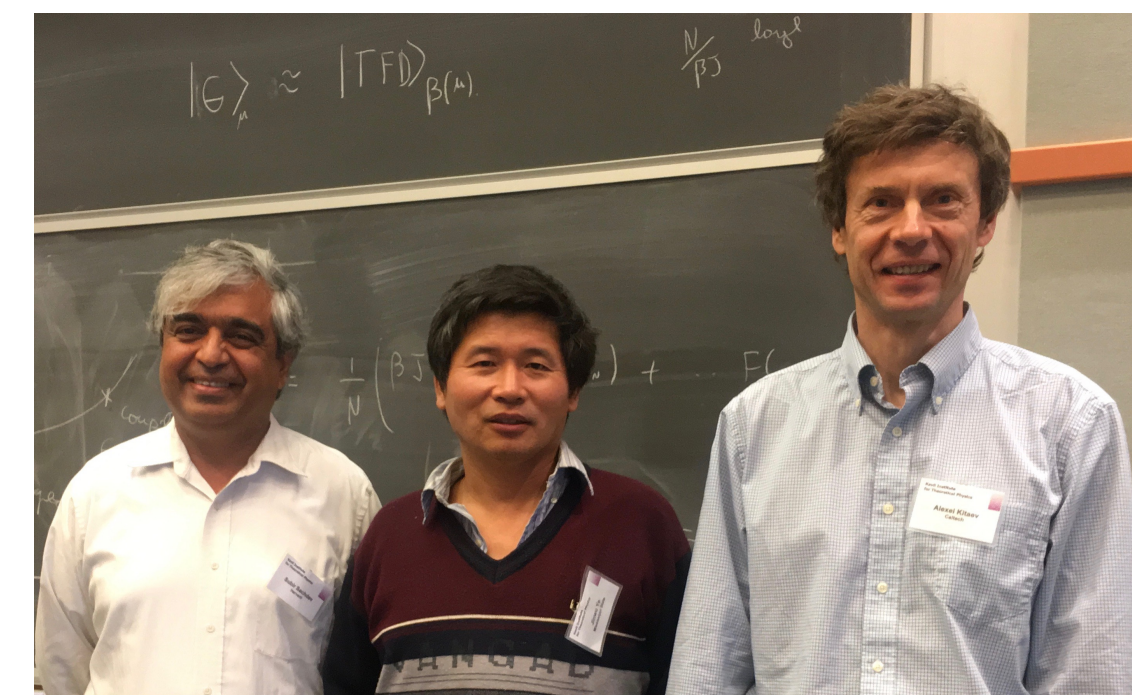


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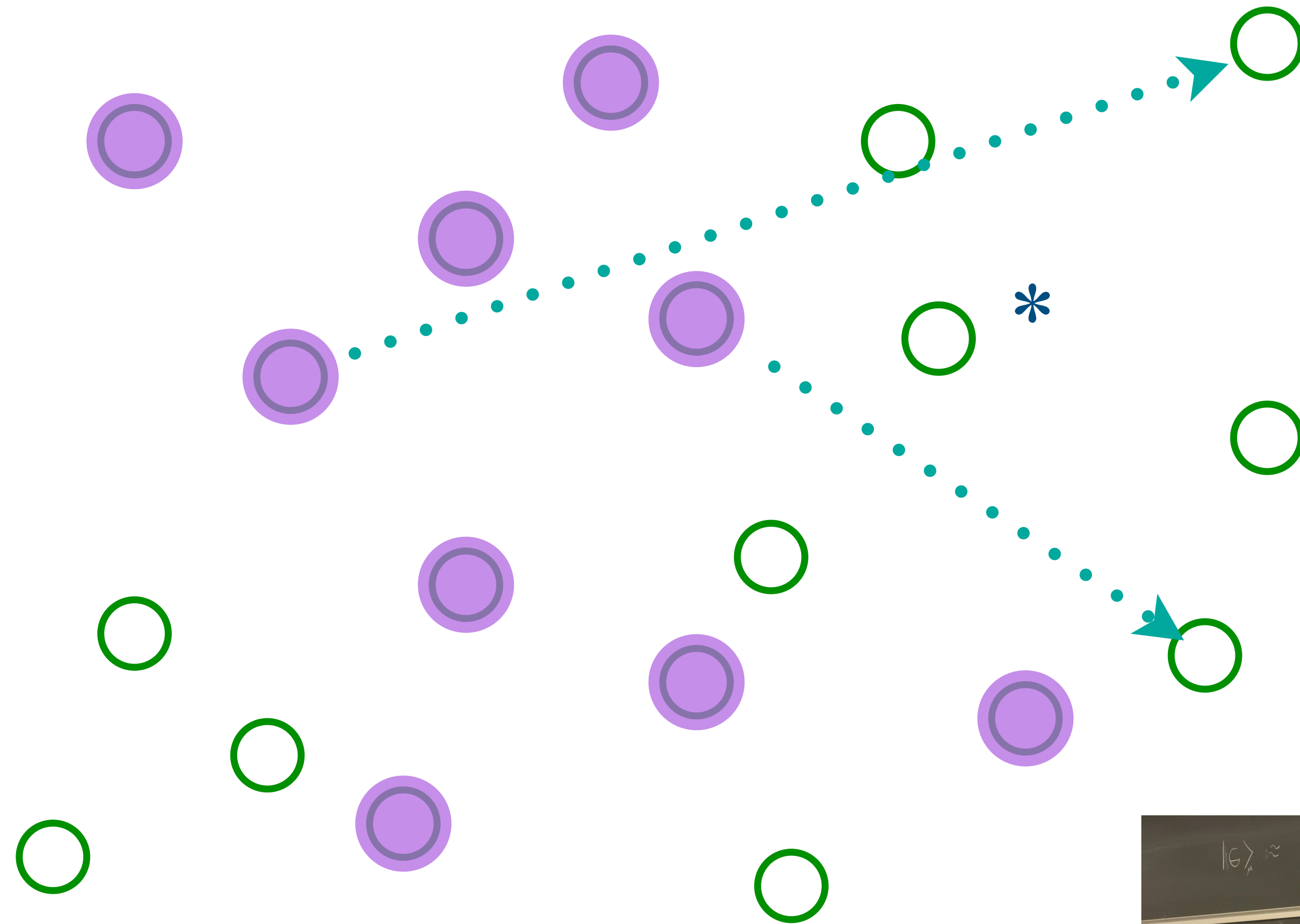


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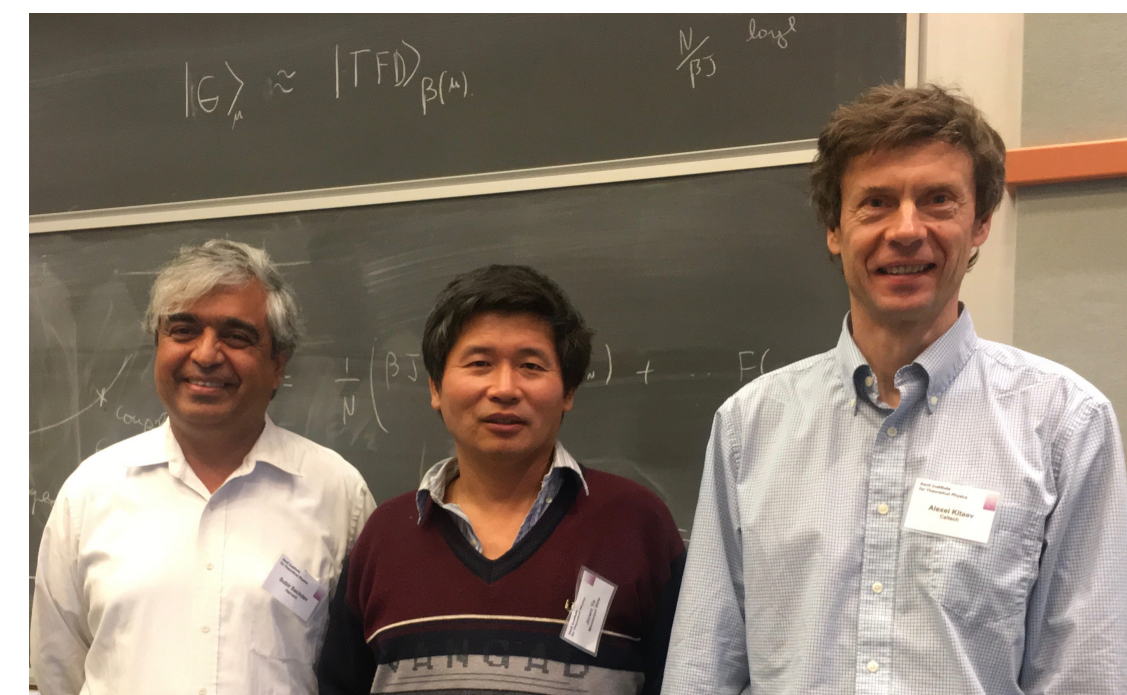


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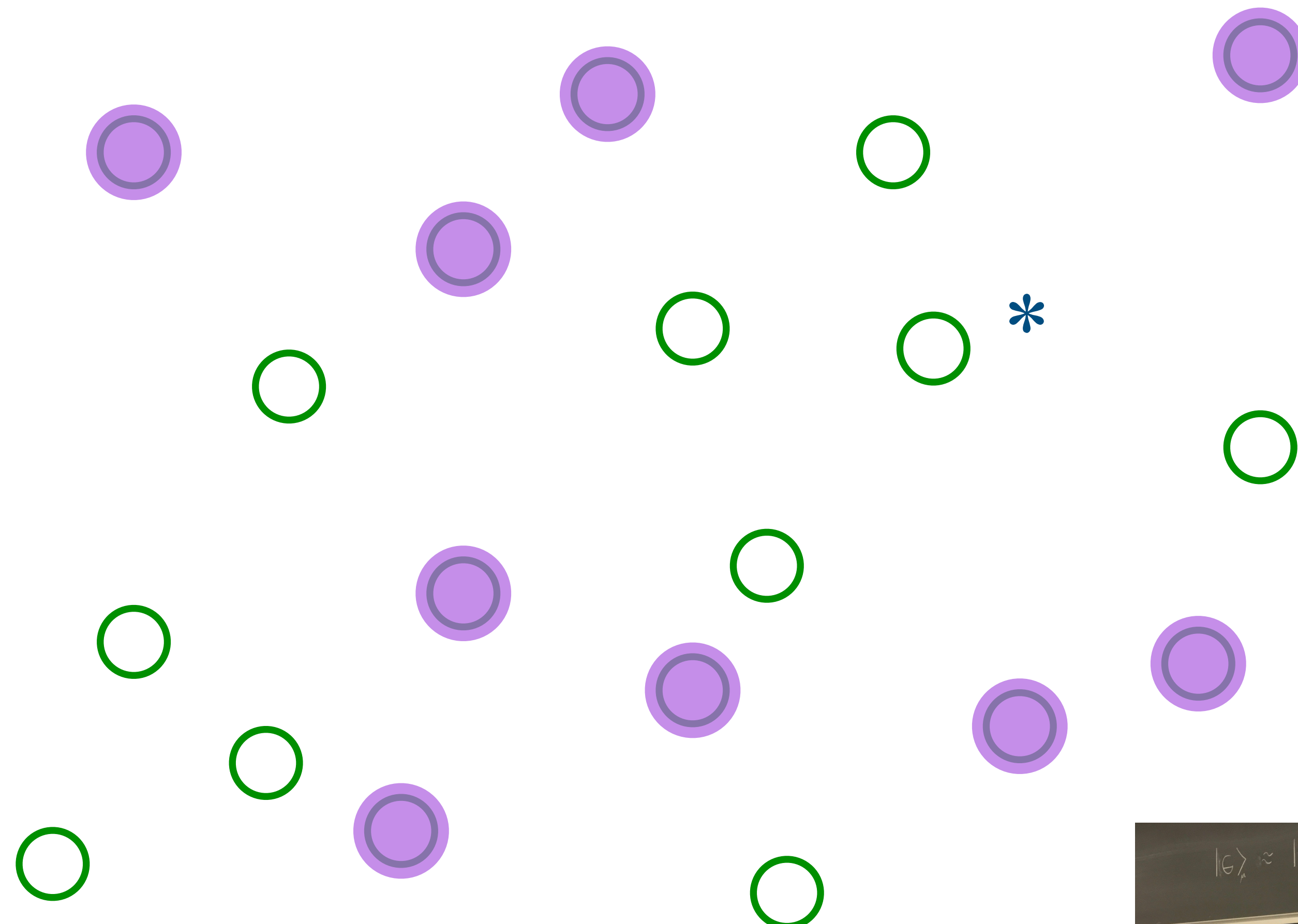


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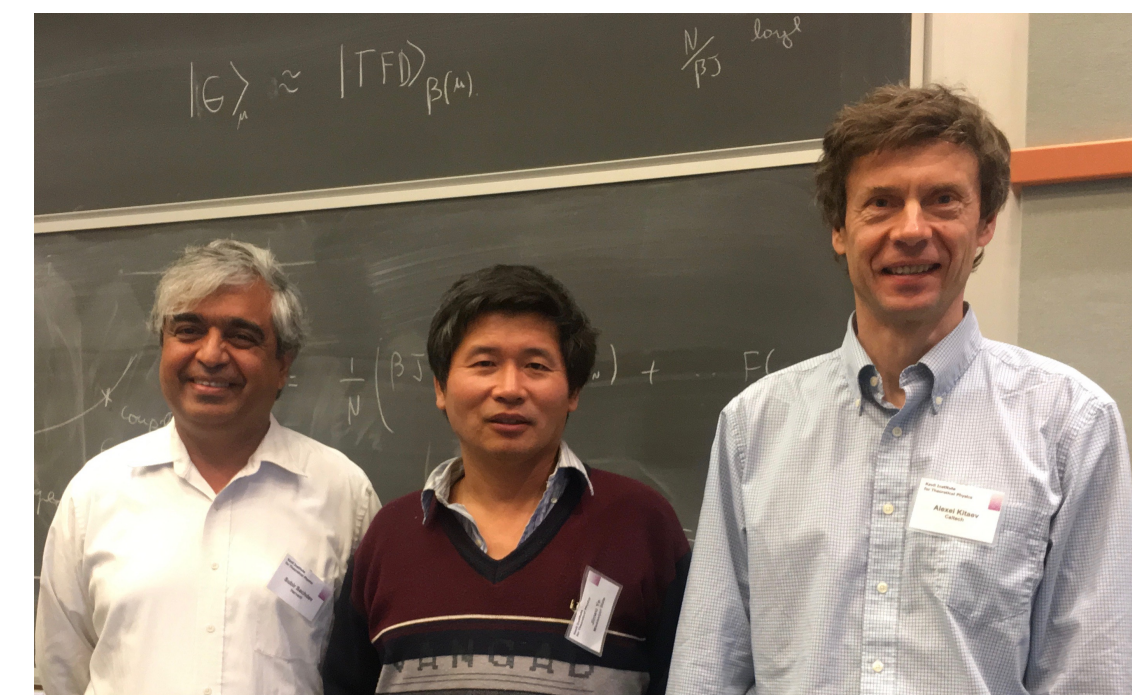


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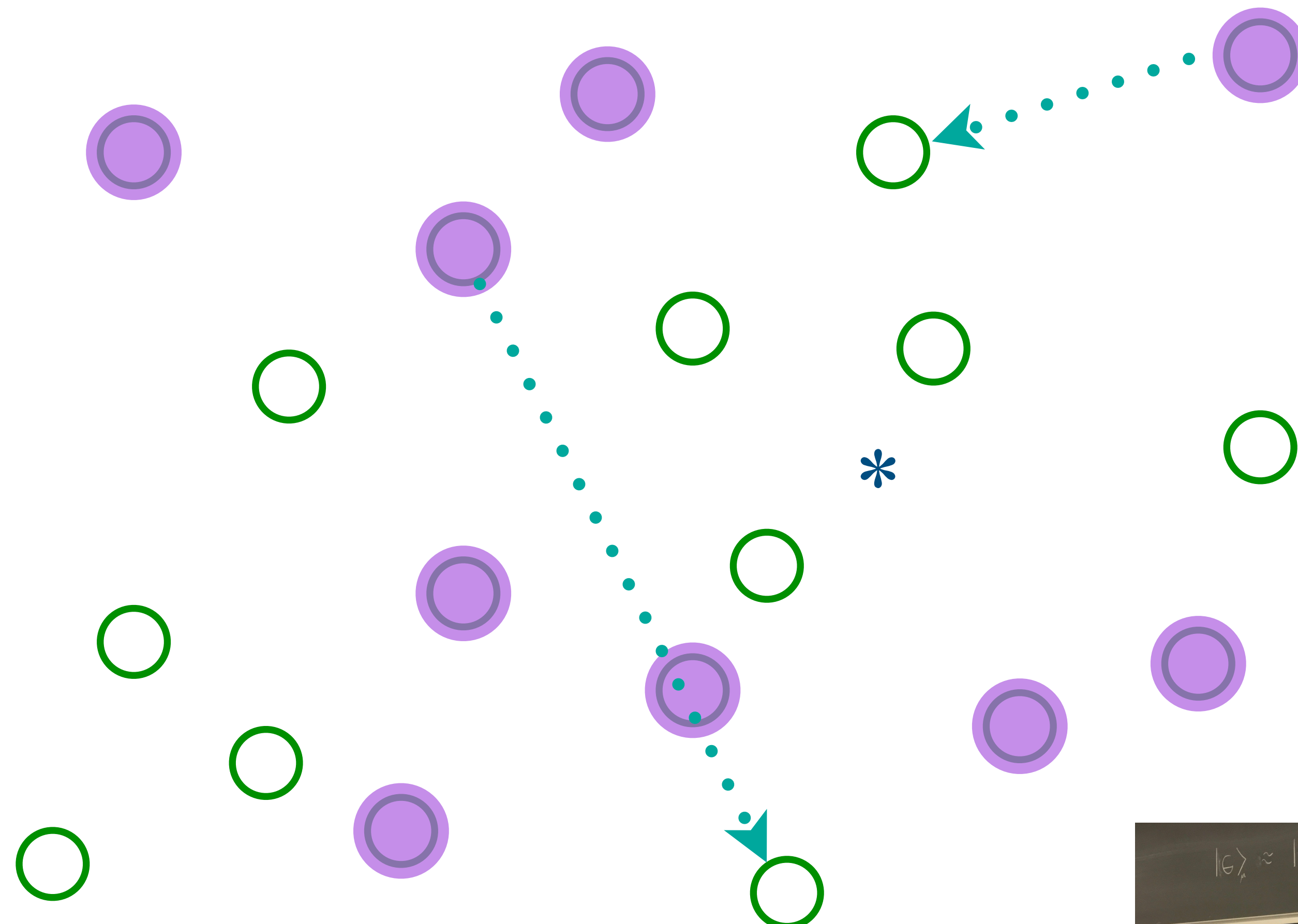


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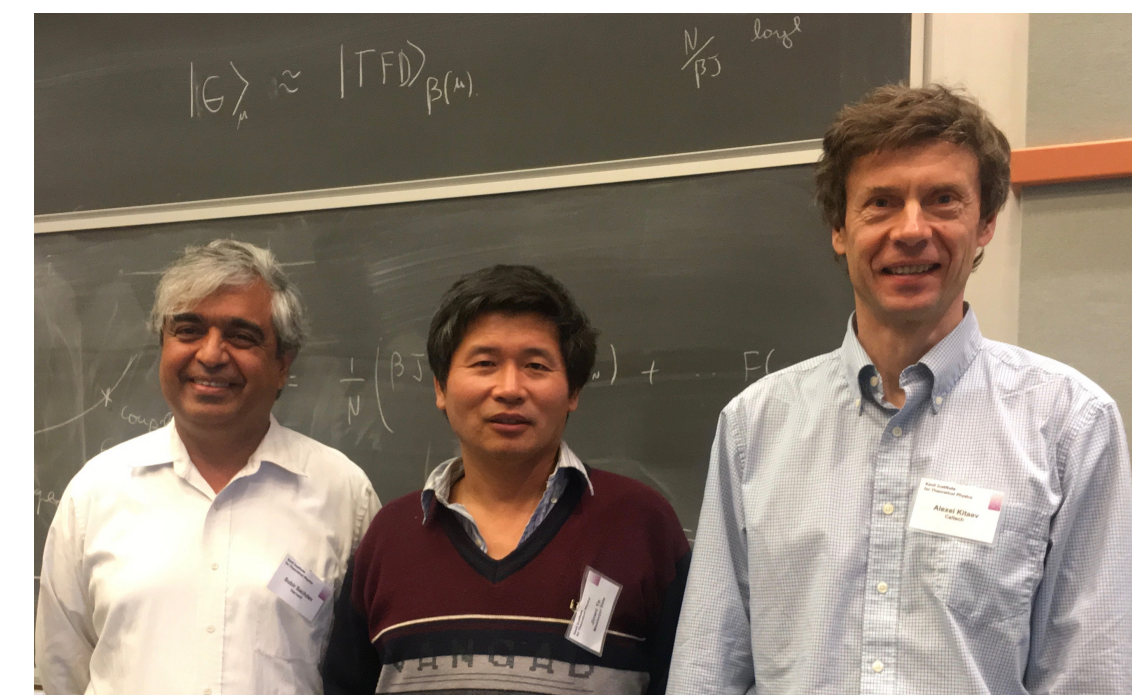


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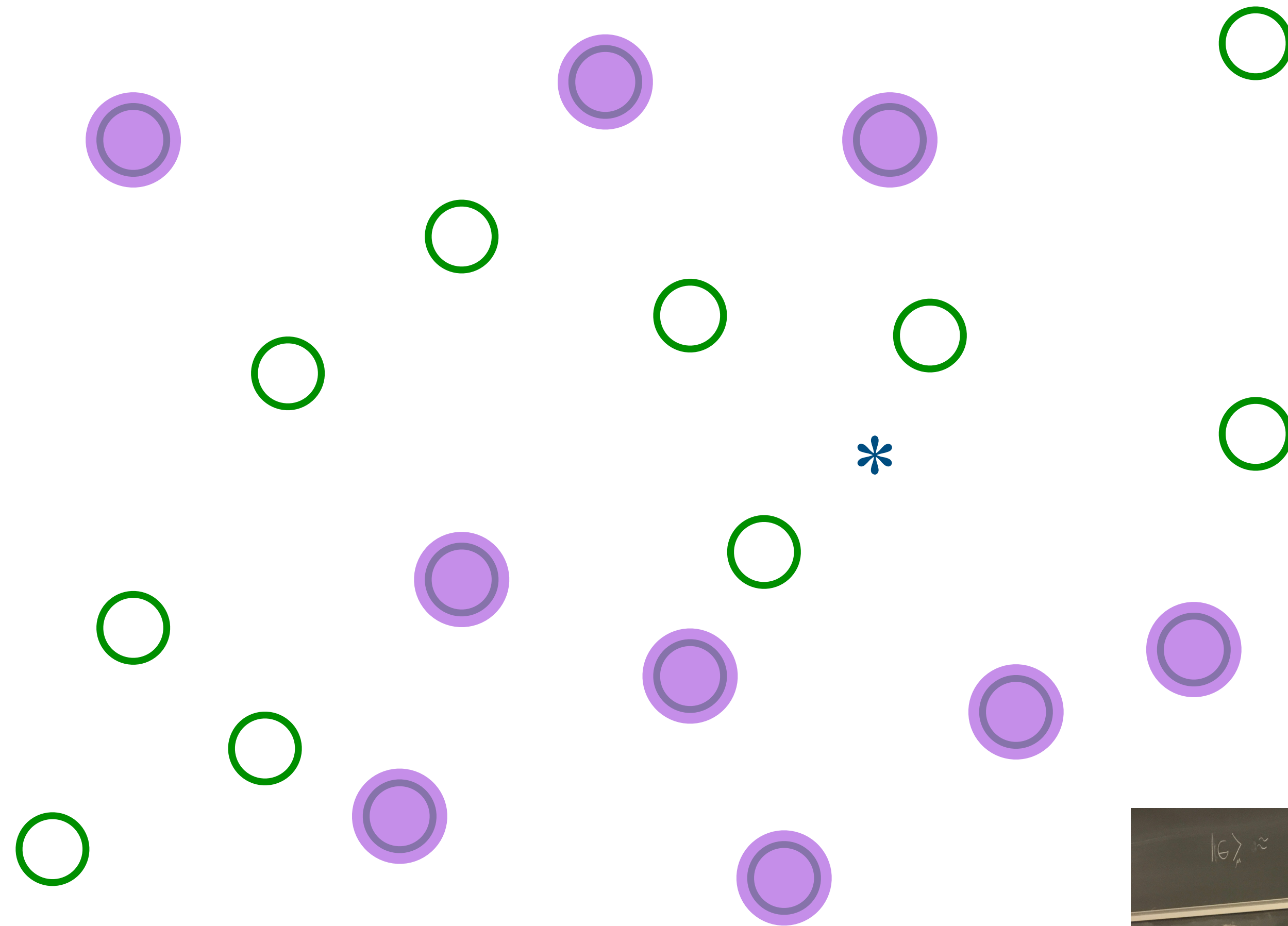


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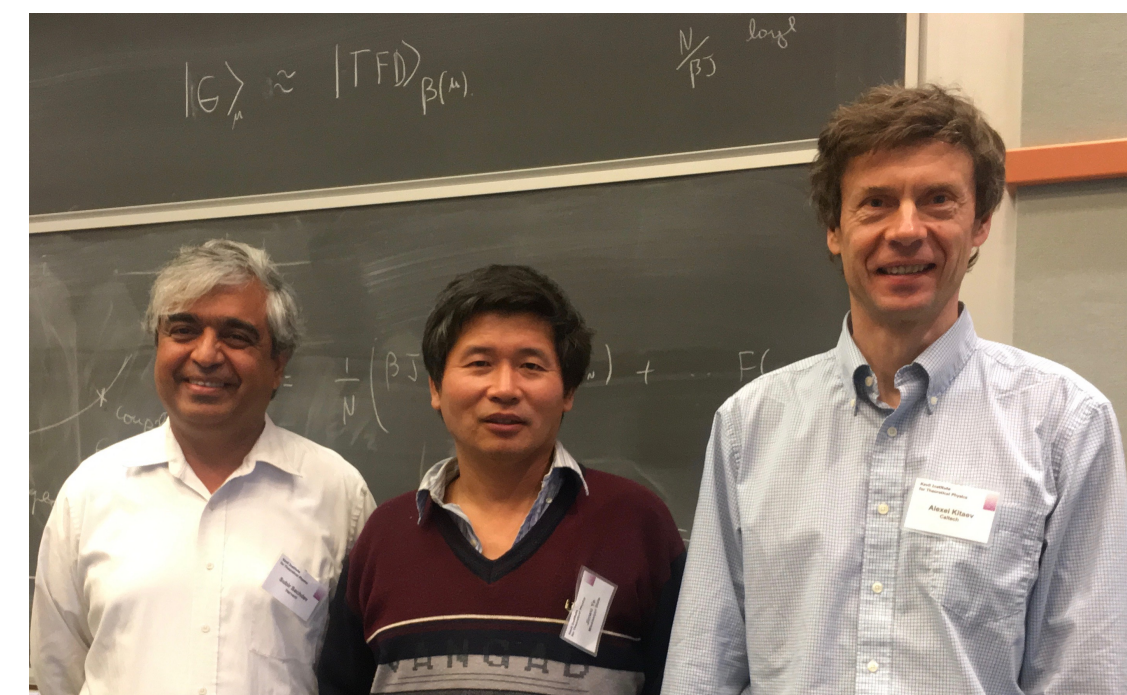


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## The Sachdev-Ye-Kitaev (SYK) model

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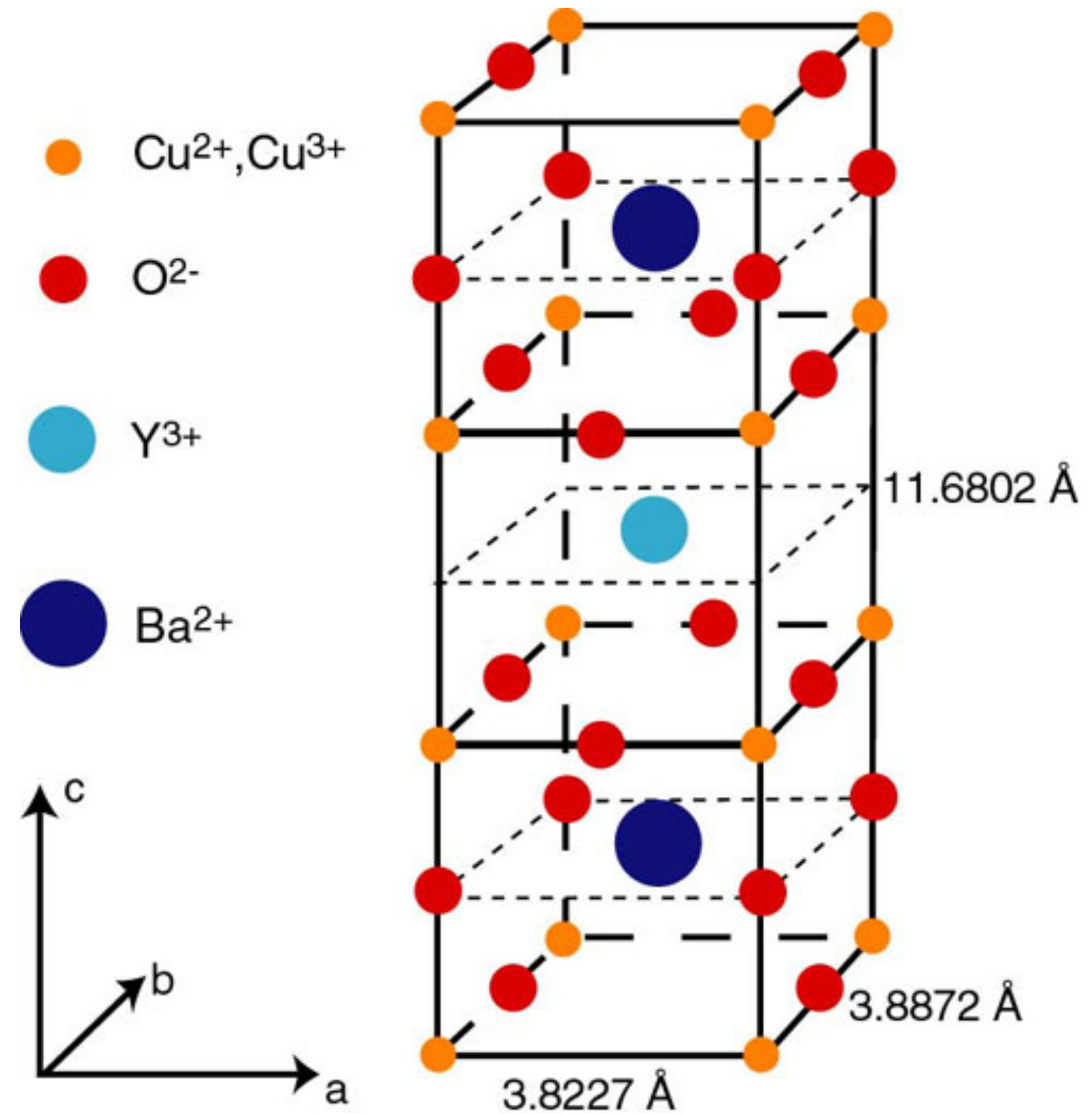
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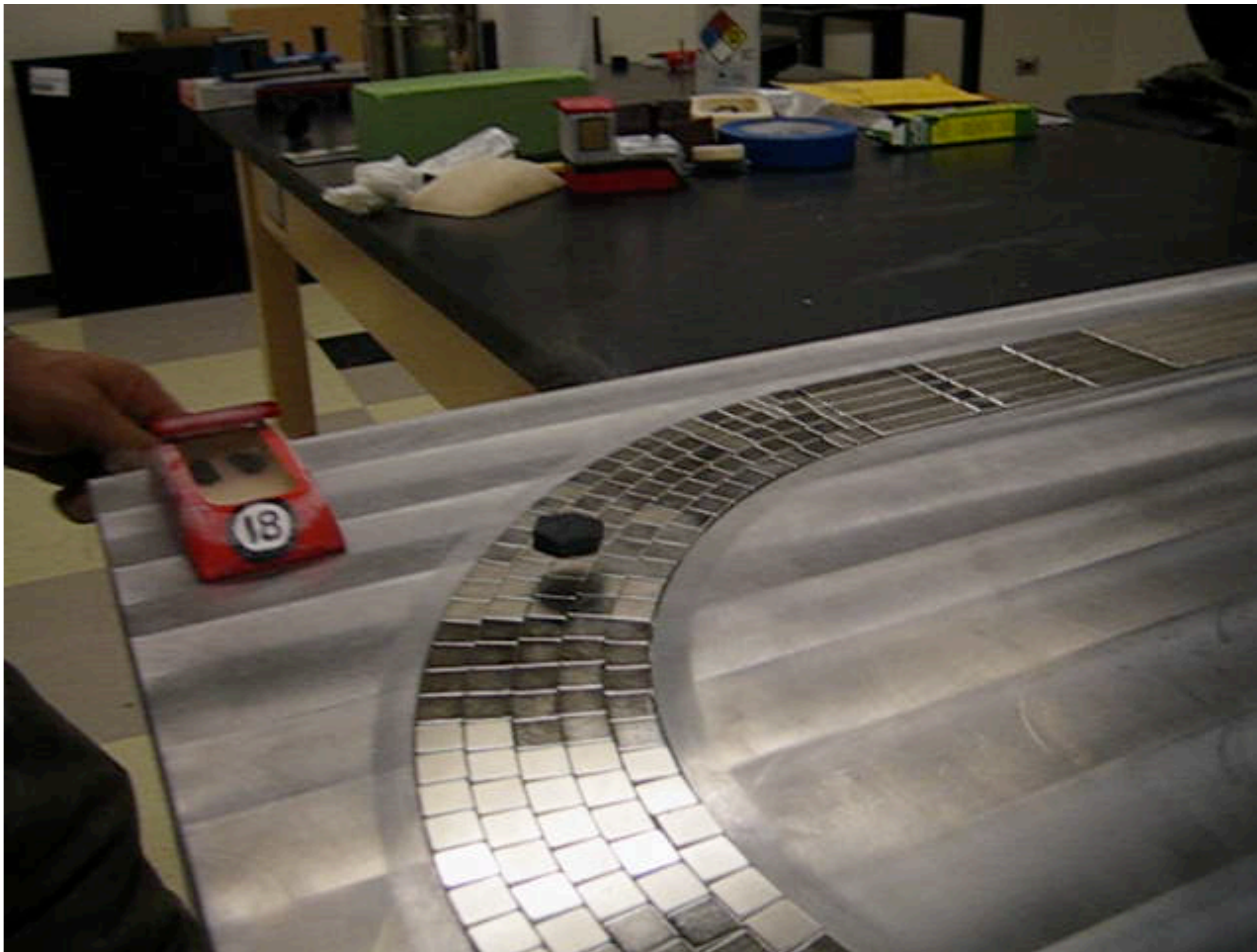


In a *dual* set of variables it describes  
charged *black holes*

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

# High temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

# HTS Magnets: Enabling Technology

A new high temperature superconductor (HTS) recently reached industrial maturity: Rare Earth Barium Copper Oxide (REBCO). CFS is using HTS and has built its first-of-its-kind high-field large-bore superconducting magnet. HTS

magnets will allow for smaller, faster, and less expensive tokamaks using the science developed on Alcator C-Mod and other tokamaks.

## The surest path to limitless, clean, fusion energy

### ● Surest

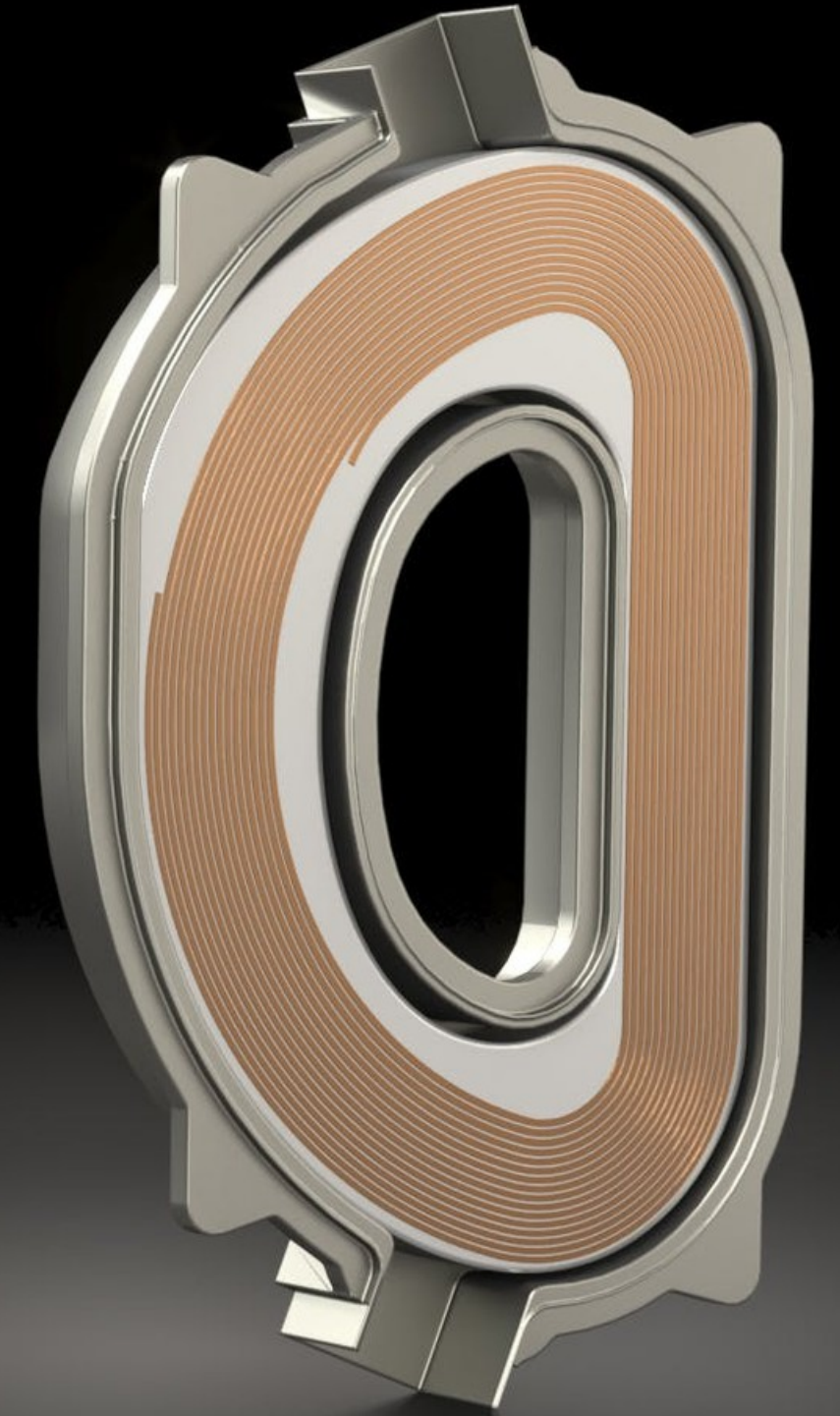
The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology.

### ○ Limitless

One glass of water will provide enough fusion fuel for one person's lifetime.

### ○ Clean

A new source of clean energy to meet our growing energy demands and combat climate change.



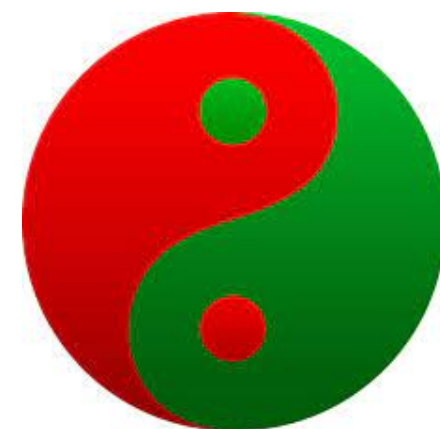
Commonwealth  
Fusion Systems

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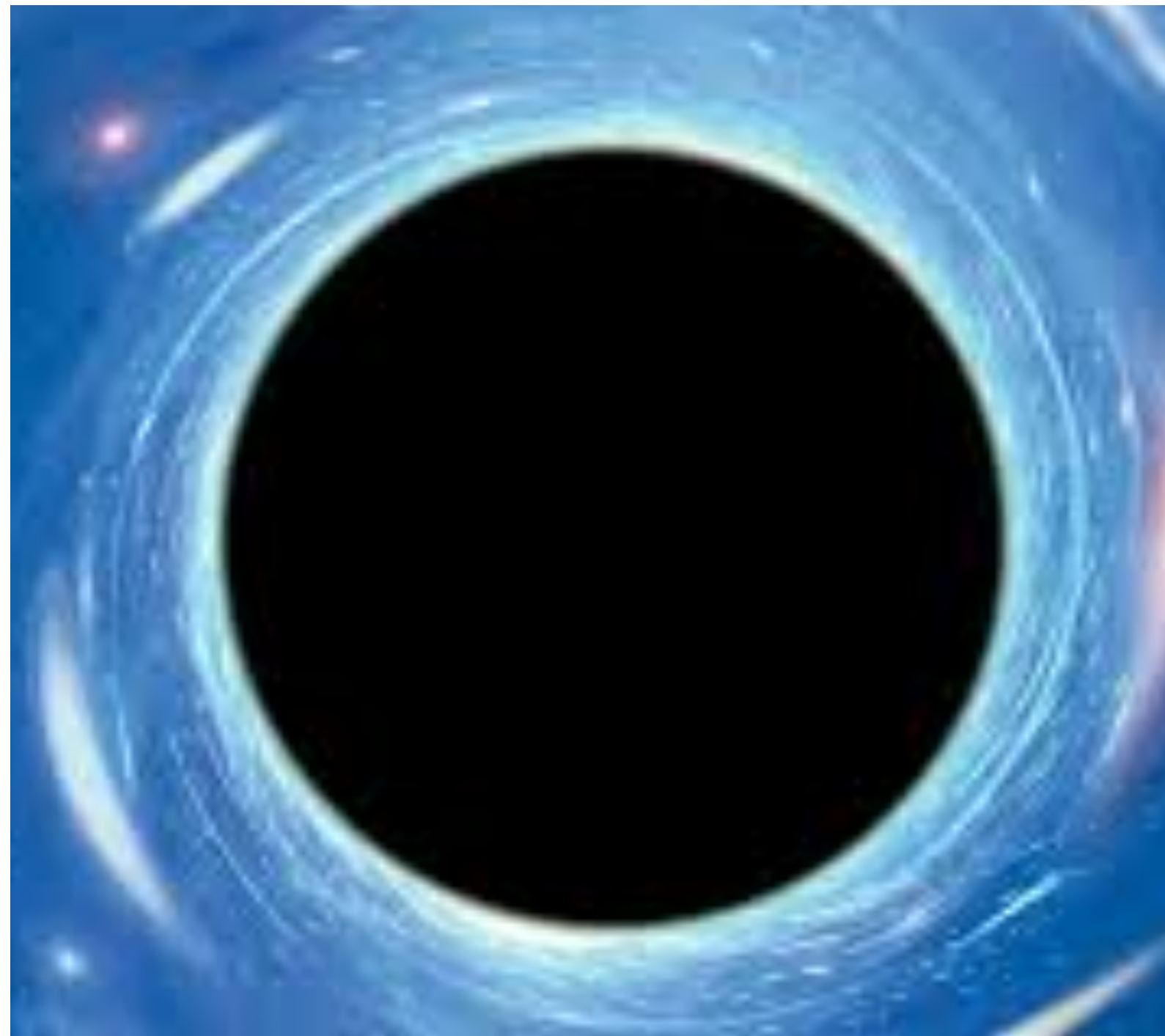


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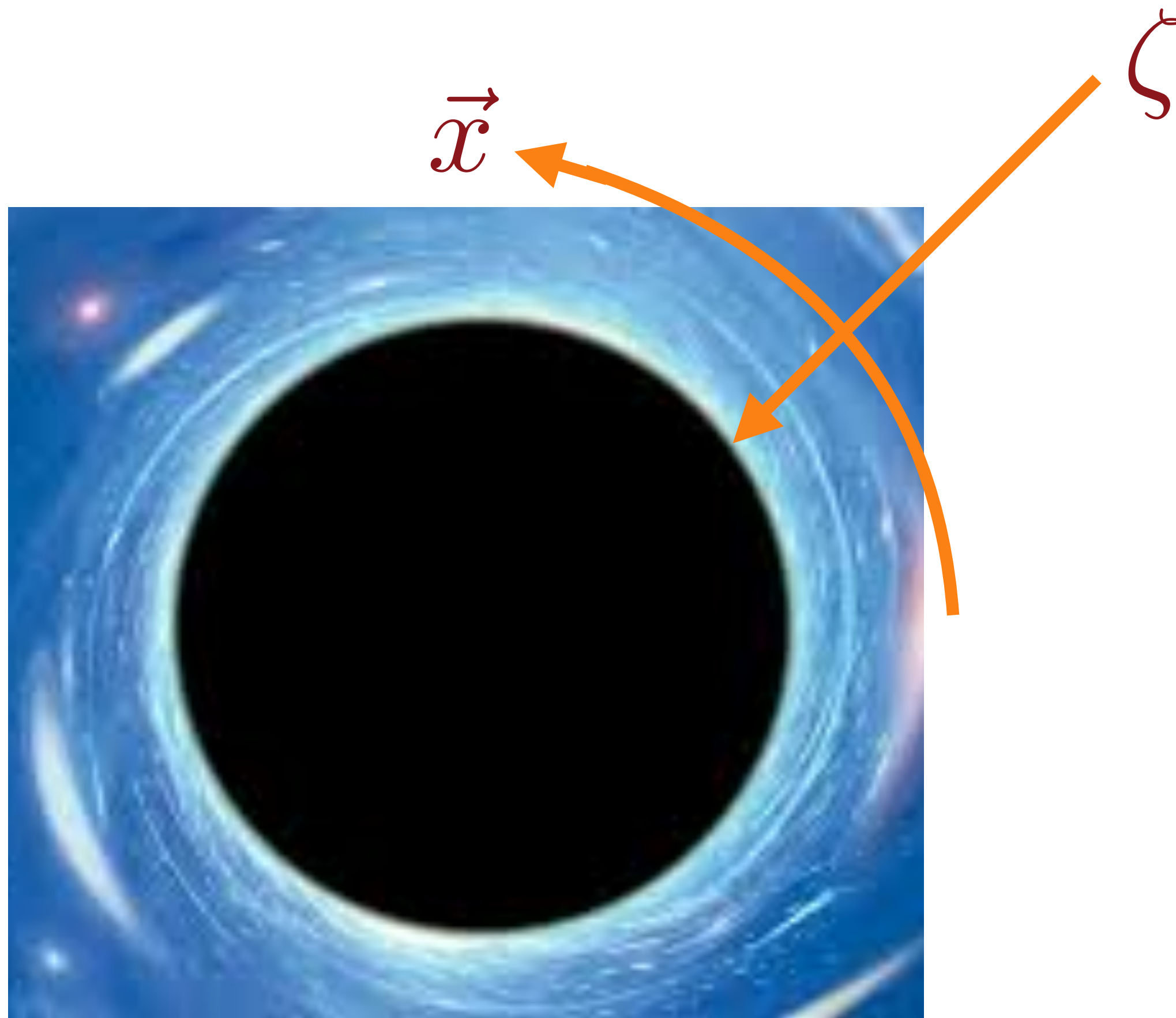


Maxwell's electromagnetism  
and Einstein's general relativity  
allow black hole solutions with a net charge





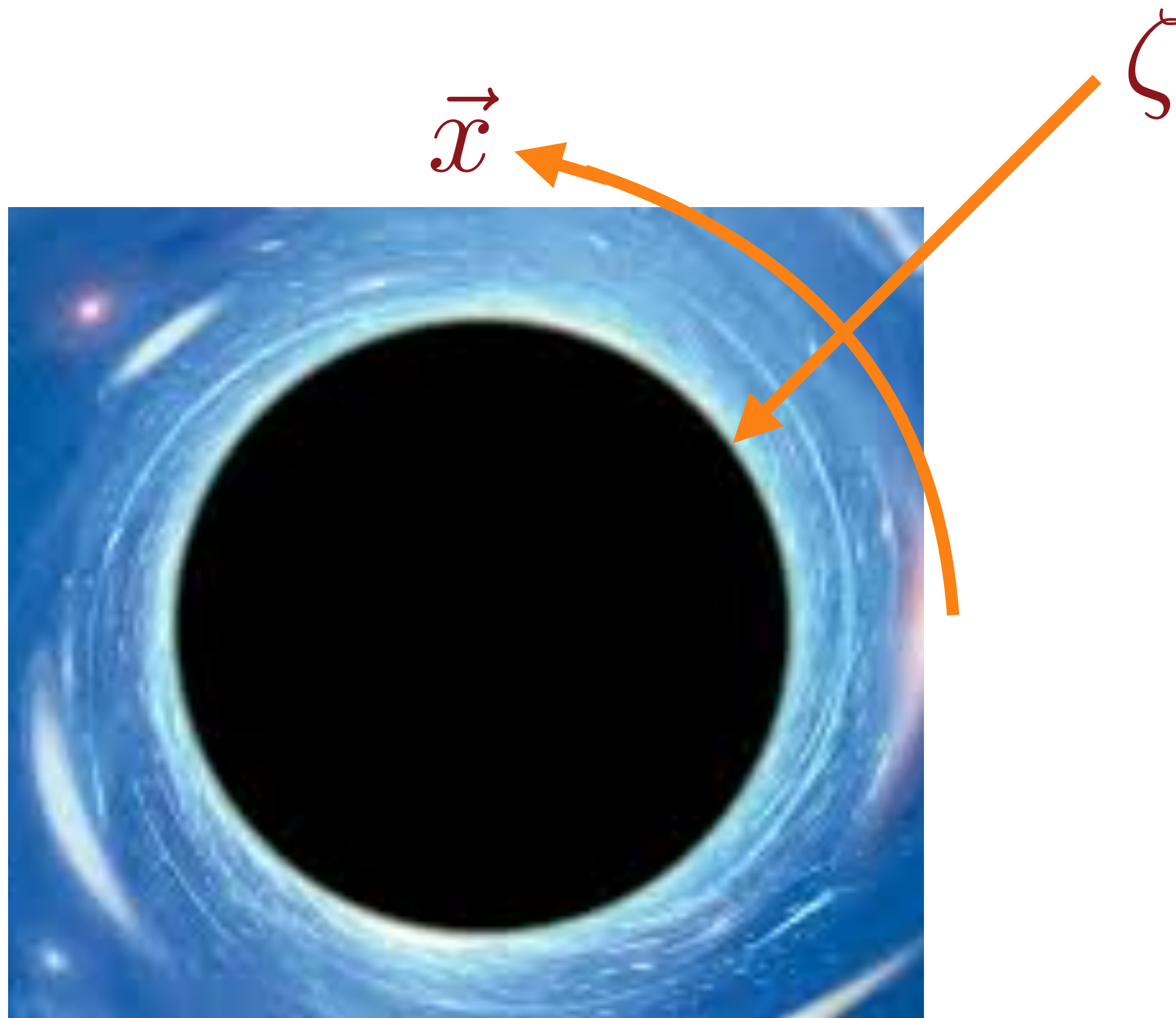
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Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space ( $\zeta$ ) and one time dimension



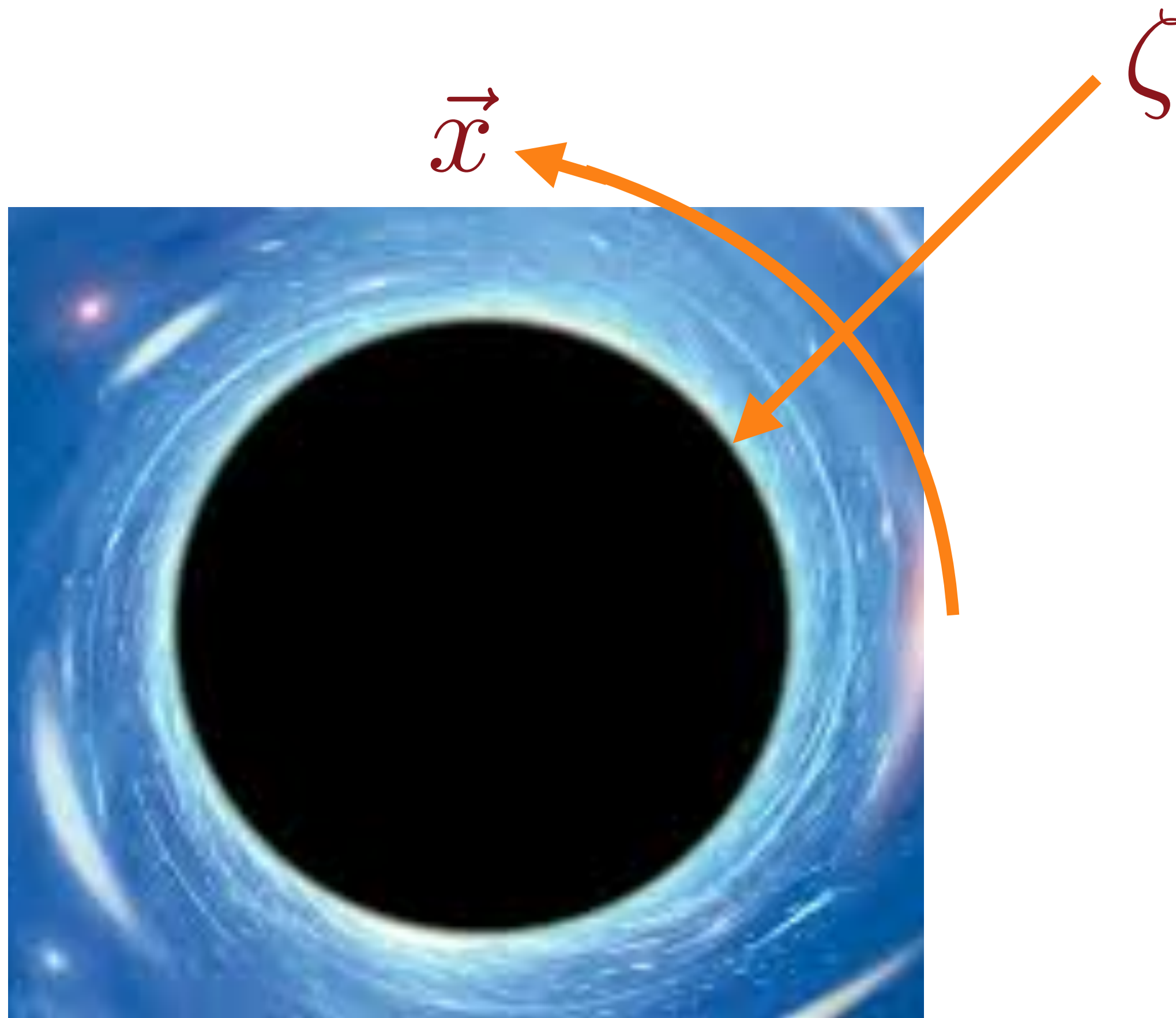
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This should be dual to a  
quantum computer in 0  
space dimensions:



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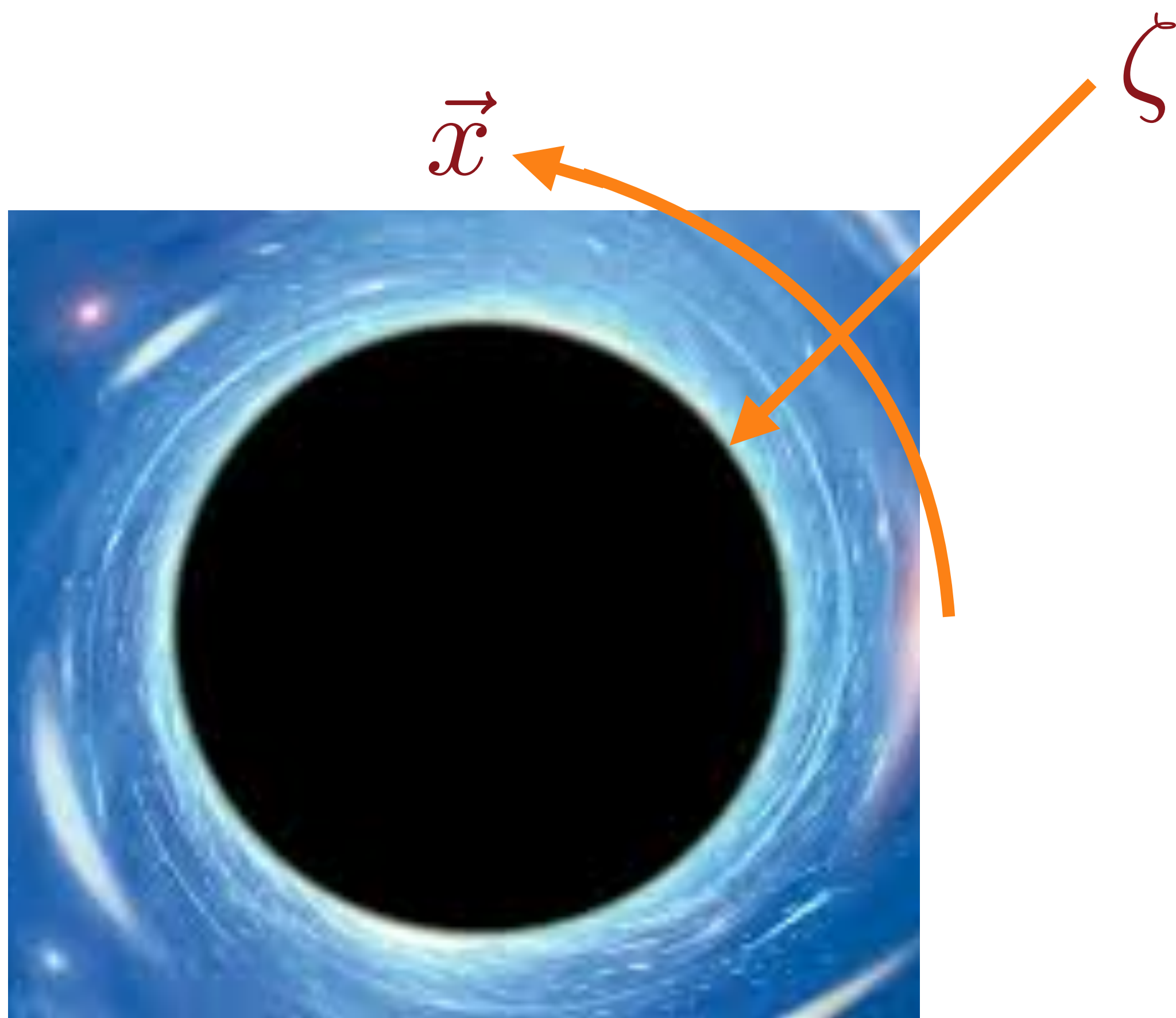


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The SYK model!



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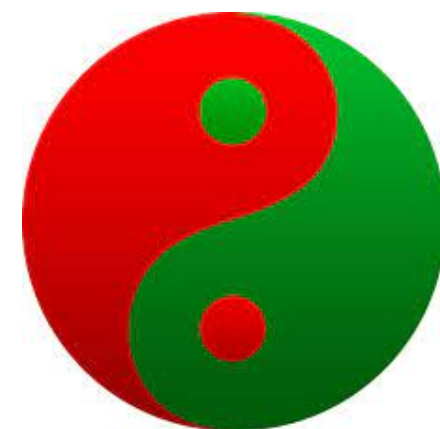
The quantum versions  
of Maxwell's and  
Einstein's equations in  
this two-dimensional  
spacetime are also the  
equations describing  
electron entanglement  
in the SYK model!

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